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MICRO-SCALE ENERGY DIRECTORS FOR ULTRASONIC WELDING

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(54) Title: MICRO-SCALE ENERGY DIRECTORS FOR ULTRASONIC WELDING

(57) Abstract: The invention relates to a replication tool (1) for producing a part (4) with a microscale textured replica surface (5a, 5b, 5c, 5d). The replication tool (1) comprises a tool surface (2a, 2b) defining a general shape of the item (4). The tool surface (2a, 2b) comprises a microscale structured master surface (3a, 3b, 3c, 3d) having a lateral master pattern and a vertical master profile. The microscale structured master surface (3a, 3b, 3c, 3d) has been provided by localized pulsed laser treatment to generate microscale phase explosions. A method for producing a part (4) with microscale energy directors on flange portions thereof uses the replication tool (1) to form an item (4) with a general shape as defined by the tool surface (2a, 2b). The formed item (4) comprises a microscale textured replica surface (5a, 5b, 5c, 5d) with a lateral arrangement of polydisperse microscale protrusions. The microscale protrusions may be provided on a flange portion of a first part (40) and are configured to act as energy directors when forming an ultrasonic joint with a cooperating flange portion of a second part (50).

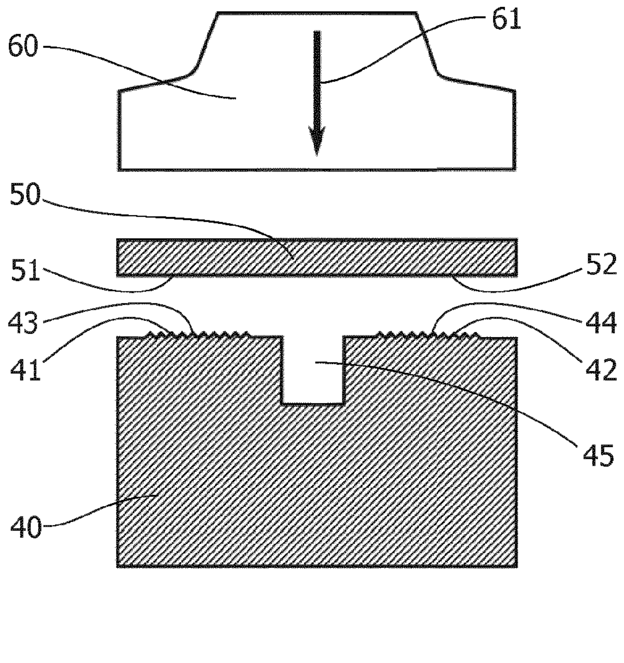

Fig. 9

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MICRO-SCALE ENERGY DIRECTORS FOR ULTRASONIC WELDING

The present invention relates in one aspect to a replication tool and a method of providing the replication tool. In a further aspect, the present invention relates to a method of producing a part by replication, the part having a flange portion for use in the formation of an ultrasonic welding joint. In yet a further aspect, the invention relates to a method of joining two parts by ultrasonic welding.

BACKGROUND OF THE INVENTION

Ultrasonic welding is a technique for joining thermoplastics parts by applying high-frequency ultrasonic acoustic vibrations across the joint surfaces while pressing the parts together. The acoustic vibrations are absorbed by the thermoplastic material, which melts locally, thereby forming a welded seam. In a typical ultrasonic welding process, at least one of the flanges of the joint comprises pointed or knife edge type protrusions, so-called energy directors that concentrate the ultrasonic energy to the location where the weld is to be formed. Energy directors commonly known from industrial processes have several disadvantages, in particular when high precision welds with high weld strength are to be formed. Examples of such applications, where high precision to form a fluid tight weld seam is essential, are microfluidic chips, such as used for medical diagnosis or environmental testing. In such applications, often a base chip with a system of microfluidic channels and components is formed e.g. as a replicated part in an injection moulding, compression moulding or hot embossing process. The base chip is then covered by a counter-part, which may equally comprise microfluidic channels and components, but may as well be a simple lid. The two parts are joined to form a fluid tight seal. Such joints may be formed e.g. by gluing, thermal bonding, or vapour bonding, but attempts have also been made to use ultrasonic bonding for joining such parts. In particular, ultrasonic bonding may overcome some of the challenges encountered with other bonding techniques, e.g. when packaging hazardous materials or sensitive reagents, where the other bonding techniques, due to the process parameters involved, are outright incompatible with the product. However, the uncontrolled deformation of the energy directors during the ultrasonic welding process typically results in the occurrence of so-called flashes that may penetrate into the microfluidic channels, or may lead to uncontrolled cross-sectional dimensions of the microfluidic channels and components.

Therefore, there is a need for a reliable and cost-effective process for forming an ultrasonic joint overcoming at least some of the above-mentioned disadvantages, or at least to provide an alternative to known methods. Furthermore, there is a need for suitable tooling for use in the above method of forming an ultrasonic joint. Furthermore, there is a need for a process for providing such suitable tooling.

SUMMARY OF THE INVENTION

A first aspect of the invention relates to a method of providing a replication tool, the method comprising providing a forming tool having a tool surface adapted to define a general shape of a part to be formed; modifying at least portions of the tool surface by a pulsed laser treatment to obtain a microscale structured master surface with a lateral master pattern and a vertical master profile; wherein the pulsed laser treatment is adapted to generate microscale phase explosions on the tool surface, thereby forming the microscale structured master surface as a lateral arrangement of microscale crater-shaped depressions. The crater-shaped depressions obtained by the microscale phase explosions are irregular in shape and polydisperse, i.e. varying in size with a spread about a most prominent size. The size may e.g. be characterized by the area covered by the depression as seen in a vertical projection on a lateral plane.

The microscale structuring of the tool surface is provided by the localized application of laser pulses directly to selected portions of the tool surface. This post-treatment of the tool surface by means of localized laser treatment has the advantage that the replication tool with the shape defining tool surface may be designed and produced using existing techniques and equipment for tool making, thereby contributing to a relatively simple and cost effective implementation of the surface modification in an existing fabrication process.

At the targeted portion of the tool surface, the localized pulsed laser treatment is adapted to melt and evaporate material at the tool surface to generate microscale phase explosions, thereby producing a randomised surface structure of polydisperse microscale features. The microscale surface features are depressions, which are typically crater shaped with steeply sloped side walls. The process of provoking microscale phase explosions by locally applying laser energy to the tool surface so as to form the crater-shaped depressions is stochastic in nature, wherein upon appropriate exposure the microscale surface features are densely packed and may even partially overlap, thereby forming a microscale lateral pattern with a microscale porous appearance. The localized application of laser power may be scanning a laser spot along a predetermined scanning path at a pre-determined scan speed over the tool surface. The path may follow a single scan along the path over the tool surface, a repetitive scanning along the same linear path, or a combination of both. The path is adapted to cover the selected portions of the tool surface. The path may e.g. be straight, curved, meandering, segmented or a combination thereof and some sections of the path may overlap other sections of the path in order to achieve an even exposure of the selected portions of the tool surface with laser energy.

The pulsed laser radiation has to be of a wave length and pulse characteristics that is absorbed by the tool surface in order to be able to locally melt and evaporate material from the tool surface so as to produce microscale phase explosions creating the crater-shaped depressions. For example, the laser radiation may be from a picosecond-laser source with a wavelength in the near infrared, such as 1064 nm, but other wavelength ranges, e.g. in the visible part of the electromagnetic spectrum, and pulse characteristics that are suitable for locally heating the tool surface to generate microscale phase-explosions may be conceived, too. The finish of the targeted portions of the tool surface is controlled by adapting the exposure of these tool surface portions with the pulsed laser radiation. The exposure of the tool surface is controllable e.g. by adjusting the laser power/spot intensity and/or by varying the scan speed, wherein exposure of a given surface portion increases with increasing laser power, but decreases with increasing scan speed. The finish of the targeted portions of the tool in turn determines the finish of the replicated part in the corresponding regions on the surface of the part via the replication process. Furthermore, multiple exposures of the same surface portions, e.g. by repetitive and/or overlapping scanning of the laser spot over these surface portions, results in an exposure that is increased correspondingly.

Preferably, the lateral pattern of the microscale structured master surface has an area density of microscale master features of at least 5000/mm². Thereby, a reasonably densely packed lateral distribution of microscale features on the master surface is achieved, thereby allowing for producing parts with a replicated microscale surface texture that is useful for forming high precision, fluid tight ultrasonic joints with improved bond strength.

Further preferably, the lateral pattern of the microscale structured master surface has an area density of microscale master features of at least 8000/mm², or even of at least 10000/mm². Thereby, a densely packed lateral distribution of microscale features on the master surface is achieved, thereby allowing for forming high precision, fluid tight ultrasonic joints with particularly improved bond strength. It should be noted that an upper limit for the area density resulting from the microscale of the surface structuring exists, which is discussed in detail further below.

A further aspect of the invention relates to a method of producing a first part having a flange portion for use in the formation of an ultrasonic welding joint with a cooperating second part, the method comprising the steps of

- providing a replication tool with a microscale structured master surface by a method according to the above-mentioned embodiment; and

- using the replication tool to form the first part by the replication process, wherein the formed first part has the general shape as defined by the tool surface, and wherein the formed first part comprises a microscale textured replica surface with a lateral arrangement of microscale cone-like protrusions on at least the flange portion of the first part.

Preferably, the lateral pattern of the microscale textured replica surface has an area density of microscale cone-like protrusions of at least 5000/mm². As mentioned above, this allows for forming high precision, fluid tight ultrasonic joints with improved bond strength.

Further preferably, the lateral pattern of the microscale textured replica surface has an area density of microscale cone-like protrusions of at least 8000/mm², or even of at least 10000/mm². As also mentioned above, this allows for forming high precision, fluid tight ultrasonic joints with particularly improved bond strength. An upper limit for the area density resulting from the microscale of the cone-like protrusions forming the surface texture exists, which is discussed in detail further below.

The method is useful for forming the first part from a replication material replicating the microscale structured master surface onto the first part to form a surface region with a lateral arrangement of polydisperse microscale energy directors shaped as polydisperse microscale protrusions on the first part. A lateral replica pattern is defined by the lateral master pattern, and a vertical replica profile has finite peak-to-peak amplitude to form a three-dimensional texture. Since the lateral replica pattern is defined by the lateral master pattern, it is equally irregular as seen in a projection onto a lateral plane, and the microscale protrusions are polydisperse. The method is for producing the first part by a fast replication process using the replication tool, such as required by a commercially viable production of the item in large numbers.

As mentioned above, the laser treatment of the tool surface results in a porous surface appearance produced by a randomised lateral arrangement of, preferably densely packed, microscale depressions, which are typically shaped as relatively deep, steep-walled craters with a more or less pointed bottom. The sloped sidewalls facilitate an easy de-moulding of the replicated item in the step of releasing the item from the tool surface.

Since the method is useful for the production of first parts by a fast replication process, it allows for a low-cost and/or mass production of the first part with a first flange portion that is prepared for ultrasonic bonding with a cooperating second flange portion on a second part by providing the first flange portion with microscale energy directors. A replication process may be considered fast, for example, if the replication period from contacting the tool surface with the molten replication material to releasing the formed part is short, such as well below ten minutes, such as less than five minutes, such as less than 3 minutes, such as less than one minute, such as less than 30 seconds, or even less than 10 seconds. In particular, the suggested thermally controlled replication process using a thermoplastic replication material can be performed fast as compared to for example replication processes using thermosetting replication materials, or chemically setting replication materials. However, the method is also useful for the production of first parts having a flange portion with microscale energy directors thereon by other replication techniques, such as the mentioned slower methods using thermosetting or chemically setting replication materials, or for replication techniques like compression moulding and hot embossing.

The term microscale refers to dimensions of about 1 µm to 1000 µm that are generally measured in microns (micrometres), typically in the range of about 1 µm to 100 µm. Accordingly, the term nanoscale refers to dimensions of about 1 nm to 1000 nm that are generally measured in nanometres, typically in the range of about 1 nm to 100 nm.

The microscale structure of the master surface and, accordingly, the microscale texture of the replica surface have a three-dimensional topography of microscale elements arranged next to each other and may be decomposed in a lateral pattern and a vertical profile. The term “lateral pattern” refers to the arrangement in lateral directions of the (3D) microscale elements making up the microscale structure/texture, as seen in vertical projection on to a lateral plane. The term “vertical profile” refers to the variation of the location of the surface in a direction perpendicular to the lateral directions.

When a surface structuring/texturing is applied to an object having a general shape, such as a tool surface or an item, the surface structuring/texturing can be seen as a vertical variation of the surface, which is added to the general shape of the tool surface/item. Accordingly, on an object with a microscale structured/textured surface, an average surface that flattens out any vertical variations of the surface by averaging on a lateral scale larger than that of the microscale structuring/texturing essentially follows the general shape of the object. The general shape of the object is thus defined independent of any nano- or microscale surface roughness / finish / structuring. At a given point on the surface of the object, lateral directions are parallel / tangential to a surface defining the general shape of the object on a scale larger than the scale of the lateral pattern. Accordingly, the vertical direction at a given point on the surface of the object is the surface normal to the general shape in that point. In each given point, the vertical direction is perpendicular to the corresponding lateral directions.

The general shape of the replicated part is defined by the general shape of the tool surface. The replication process is for accurately replicating the general shape of the part as defined by the tool surface. The surface of the replicated part is functionalised by applying a surface finish with a microscale texture at least on selected regions of the surface of the part. The particular functionalization is to make a flange portion of the replicated part susceptible to concentrate ultrasonic energy so as to act as a distributed energy director when forming an ultrasonic joint with a cooperating flange portion of a counterpart. To concentrate the ultrasonic energy applied across the interface between the first and second flange portions, the area of contact is reduced to point contacts where the tops of the protrusions meet the surface of the counterpart when the first flange portion is brought in contact with the cooperating second flange portion.

The protrusions are sacrificial; Upon formation of the joint, the protrusions are flattened out by the ultrasonic energy dissipated and the pressure applied. The material of the energy directors spreads in lateral directions, but is easily absorbed on the spot also on a microscale, due to the lateral interspaces between the protrusions. Thereby, the quality and precision of the ultrasonic joint is improved, and the formation of undesirable “flashes”, i.e. the spreading of material into regions adjacent to the ultrasonic joint, is avoided.

An important advantage of the present method is that the laser treatment of the tool surface is only limited by the requirement of an optical access to the surface to be modified. Consequently, a microscale structured master surface may be applied to virtually any surface topology, including very narrow and deep trenches or holes, as long as a laser beam can be guided to the tool surface to be modified. This allows for an improved freedom for designing the ultrasonic joint and accordingly for designing the replicated parts to be assembled. Furthermore, at the choice of the designer, the microscale protrusions may be distributed over the entire flange portion of the replicated parts or only to selected regions thereof. Also, the flange portion may be arbitrarily shaped as seen in the lateral direction, e.g. the flange portion may easily be adapted to cover larger surfaces. The microscale energy directors may even be arranged on curved and/or oblique surfaces following a more complex general shape of the replicated part, thereby adding to the above-mentioned improved freedom of design.

According to some embodiments, the method comprises the steps of (a) providing a replication tool having a tool surface adapted to define a general shape of the first part, wherein the tool surface comprises a microscale structured master surface obtained by localized pulsed laser treatment of the tool surface to generate microscale phase explosions, said microscale structured master surface having a lateral master pattern and a vertical master profile; (b) contacting the tool surface with a replication material in the melt phase, wherein the tool surface is maintained at a process temperature below a melt temperature of the replication material, thereby (c) cooling the replication material to a stabilized shape with a microscale textured replica surface, wherein the lateral master pattern defines a corresponding lateral replica pattern of the microscale textured replica surface and wherein the amplitude of a vertical profile of the microscale textured replica surface is in the microscale, and (d) releasing the shaped item from the tool surface.

A replication process, where the tool surface is maintained at a more or less constant temperature below the melt temperature throughout the production process is sometimes referred to as an “isothermal” type process. Isothermal processes may be performed at high throughput. As also mentioned above, the truthfulness of the replication of the vertical profile of the microscale master structure is uncritical as long as the peak-to-peak amplitude of the vertical profile of the micro-texture on the replica surface is sufficient, and further preferably the lateral pattern is faithfully transferred.

Alternatively, e.g. in a so-called variothermal injection moulding process, the microscale structured master surface is prior to contact with the replication material heated to an injection temperature above the melting temperature of the replication material, but immediately upon injection of the replication material rapidly cooled to a temperature below the melting temperature of the replication material, at which the first part is finally released from the mould.

Further according to some embodiment the replication process is one of injection moulding, hot embossing, compression moulding, and extrusion coating.

Further according to one embodiment of the method, the microscale textured replica surface has a peak-to-peak amplitude of at least 0.5µm, or at least 1µm and up to 5µm, or up to 10µm, or even up to 30µm. A minimum vertical profile required to form a 3D textured surface suited for forming point contacts between cooperating first and second flange portions. To achieve a concentration of the ultrasonic energy to point contacts, the exact 3D-shape of each of the microscale features on the tool surface and their exact arrangement with respect to each other is not critical. Also, the exact details of the individual microscale elements and of their arrangement making up the micro-texture on the surface of the replicated item are uncritical for achieving a concentration effect by the microscale energy directors. The fast replication process thus yields proper items as long as the general shape is faithfully obtained reliably, the microscale lateral pattern is reliably reproduced in each reproduction process, and the peak-to-peak amplitude of the vertical profile of the replica surface is adapted to provide point contacts between the tops of the protrusions on the first part and the cooperating flange portion of the second part. Reduced amplitude gives less “flashes”, but requires corresponding precision in the flatness/fit of the cooperating first and second flange portions. Relatively small amplitudes of the vertical profile of the texture of the replica surface may already achieve a sufficient concentration of ultrasonic energy into point contacts, such as amplitudes of at least 100nm, alternatively at least 200nm, alternatively at least 500nm, and preferably in the microscale, such as 1µm-100µm, such as 1µm-30µm, preferably in the range 1µm-10µm. For ensuring a good production yield it is therefore sufficient to control the lateral scale of the texture which is well controlled by the lateral scale of the pattern of the master surface – and ensuring that the amplitude of the profile of the texture on the replica surface exceeds the local flatness of the cooperating flange surface so as to reliably form distributed point contacts between the top of the protrusions and the surface of the counterpart. A further important insight therefore relates to the nature of the fast replication process. Here, it is exploited that the lateral pattern of the microscale master structure on the tool surface is inherently reproduced with high fidelity on the replicated item. The fidelity of replication of the vertical profile on the other hand tends to be affected by standard parameters of processes for fast replication in thermoplastic materials, such as tool temperature, replication period, and temperature and/or pressure of the thermoplastic replication material in the melt phase. This is owing to the ability of the thermoplastic replication material to fill the depressions of the relatively deep steep-walled master structure before solidifying, which may be controlled by these parameters. Thereby, the fidelity of replication may be controlled. For example, fidelity of microstructure replication may be reduced by reducing the temperature at which the tool surface is maintained. When the replication material contacts the tool surface at the lower the melt is cooled more rapidly, thereby increasing the viscosity of the melt and impeding the filling of the microscale depressions/crevices/craters/pores of the master structure on the tool surface by the melt before it solidifies. A reduced fidelity is reflected by a reduced amplitude of the replicated profile as compared to the master profile: the replication is more shallow than the master. The fidelity of replication of the vertical profile may thus be characterised e.g. by comparing the peak-to-peak amplitudes of the vertical profiles of the replicated microscale texture and the microscale master structure to each other, wherein for a low fidelity replication the amplitude of the replicated profile as compared to the master profile is lower than for a higher fidelity replication. Typically, the low-fidelity replicated microscale textures exhibit a rounded top. Since the energy concentration is uncritical as to the exact shape and arrangement of the individual microscale features, another advantage of the method is that it facilitates a relatively simple and cost effective implementation of the surface functionalization in an existing fabrication process by merely modifying the tool surface of a replication tool in a post-treatment step.

Further according to one embodiment of the method, the lateral pattern of the microscale textured replica surface has an area density of microscale cone-like protrusions of at least 5000/mm², at least 8000/mm², or at least 10000/mm². Preferably, the protrusions are densely packed to provide a good mechanical strength of the joint. Furthermore, a densely packed lateral arrangement of the protrusions also ensures good fluid sealing properties of the ultrasonic joint, e.g. when forming hermetically sealed chambers or channels.

Note that the part may be made entirely from replication material with a shape defined by the tool surface, or the replication material may be applied to/carried by a substrate material, e.g. in an additive moulding step or a coating step.

Further according to one embodiment of the method, the replication process used for producing the part is injection moulding. Injection moulding is a cyclic replication process with a fast cycle time, i.e. using this embodiment a large number of separate items with a microscale textured replica surface may be produced at high throughput. The inner surface of the injection mould is the tool surface defining the general shape of the part. At least portions of the tool surface have a finish with a microscale structuring generated by localised treatment with a pulsed laser source. The thermoplastic replication material is heated to above the melt transition temperature and in the melt phase injected into the closed mould, which is kept at a temperature between the glass transition temperature and the melt transition temperature of the replication material. When the molten replication material contacts the cooled tool surface it solidifies, whereby it is shaped and textured, before the item is released from the mould.

A surprising insight is that the replica surface produced in a fast injection moulding process using the replication tool presented herein exhibits a microscale textured replica surface which is well suited for forming a reliable ultrasonic welding joint also if the vertical profile of the microscale texture on the replica surface is a low fidelity replication of the corresponding profile of the microscale structure on the master surface. Precise and strong ultrasonic welding joints may be reliably obtained as long as the lateral pattern is faithfully transferred and the peak-to-peak amplitude of the vertical profile of the micro-texture on the replica surface is in the microscale, or at least has an amplitude that is sufficient for forming point contacts that are distributed over the respective flange portions. Thereby, a robust low-cost mass-production process for parts is achieved, which are suited for being joined to other parts by ultrasonic welding, and even form a fluid tight seal.

In another particularly advantageous embodiment of the method, the replication process is extrusion coating. Extrusion coating is a process for roll-to-roll processing, i.e. using this embodiment the part may be produced in a continuous process as a layered web with a microscale textured replica surface. To that end, a substrate web may be passed between a nib roll and a cooling roll, in a conventional manner, wherein the rotary surface of the cooling roll is the tool surface defining the general shape of the item. The tool surface has a finish with a microscale structuring generated by treatment with a pulsed laser source. A thermoplastic replication material is heated to above the melting temperature and in the melt phase supplied between the substrate web and the cooling roll, which is kept at a temperature below the melting temperature of the replication material. When the molten replication material contacts the cooled tool surface it solidifies, whereby it is shaped and textured, before the item is released from the replication tool.

Further according to one embodiment of the method for producing a part with microscale energy directors on flange portions thereof, a replication period from contacting the tool surface with the molten replication material to releasing the shaped item is less than 3 minutes, such as less than one minute, such as less than 30 seconds, or even less than 10 seconds. Typically, in an injection moulding process, the replication time may be less than one minute, i.e. a few tens of seconds, such as about 30 seconds. Typically, an extrusion coating process is even faster with replication times of less than 10 seconds.

Further according to one embodiment of the method for producing a part with microscale energy directors on flange portions thereof, the vertical replica profile predominantly has rounded tops with a radius of curvature in the microscale. As described above, the replication process may be controlled to influence the fidelity of replication to provide a vertical replica profile that predominantly has rounded tops with a radius of curvature in the microscale. A low fidelity replication may be achieved in a fast replication process with short replication periods. A process goal/constraint of a faithful replication of the vertical profile of the master structure, on the other hand may entail long settling or curing times incompatible with a fast replication process.

Advantageously, the radius of curvature of the rounded tops is of the same order as the lateral distance between adjacent structures/features of the lateral pattern, such as predominantly above 1μm, above 5μm, or even above 10μm, and predominantly less than 300 μm, less than 100μm or even less than 50μm. Further advantageously, the vertical amplitude of the replica profile is about equal or less than the lateral distance between adjacent microscale features.

In a further aspect, a method for producing a part with microscale energy directors on flange portions thereof comprises preparing a replication tool using the above-mentioned method, and repeatedly performing the method of producing an item with a microscale textured replica surface by a replication process according to any one of the above-mentioned embodiments. Large numbers of items exhibiting enhanced hydrophobicity or super-hydrophobicity may thus be produced cheaply.

According to a further aspect, the invention relates to a part with a microscale textured replica surface produced by replication according to any of the above-mentioned methods.

According to a further aspect, a method of joining a first part and a second part by ultrasonic welding, comprises the steps of

- producing the first part with microscale energy directors in the form of microscale cone-like protrusions on a flange portion thereof by the method according to any one of the above-mentioned embodiments;

- producing a second part having a cooperating flange portion;

- bringing the microscale cone-like protrusions on the flange portion of the first part in contact with the cooperating flange portion of the second part; and

- applying ultrasonic energy and pressure, thereby flattening out the cone-like protrusions, to form an ultrasonic welding joint between the first and second parts.

The ultrasonic energy is applied across the flange portions while applying a compression force pressing the two cooperating flanges together. In contrast to energy directors commonly used for forming ultrasonic joints, the invention provides areas of microscale energy directors distributed over flange portions where the work pieces are to be welded together. According to the present invention, a master of the micro-scale energy directors is produced by at least partially covering corresponding flange portions of the work piece negative in a forming tool with a micro-scale roughening, and subsequently replicating the microscale roughening into the flange portions of the work pieces in a forming step. It has turned out that the above described pulsed laser treatment of the tool surface gives an adequate microscale roughening that may be replicated onto the part to form micro-scale energy directors. In particular, by tuning the laser treatment to generate “microscale phase explosions” when applied to tool surfaces, such as forming steel surfaces or aluminium tool surfaces/inserts), a proper scale of the depressions is obtained. By using laser processing of the tool surface a welding joint portion may even be defined on the forming tool in a post processing process, e.g. on an existing forming tool, independent of the process of preparing the forming tool / tool surface. By applying the micro-scale roughening to the tool, the welding joint portion may be produced in the same replicating step as the part itself. The master surface has a microscale structuring with a lateral master patterning and a vertical master profile. Accordingly, the replicated part has a microscale texture with lateral replica patterning and a vertical replica profile.

Further according to some embodiments of the method of joining first and second parts, at least one of the first part and the second part is made of a thermoplastics material.

Further according to some embodiments of the method, the first part comprises a flexible web carrying the microscale textured replica surface with a lateral arrangement of microscale cone-like protrusions on at least a flange portion thereof. For example, such embodiments may be useful for assemblies comprising a functionalized flexible web integrated therein, or for packaging purposes, or when using the flexible web as a cover for a closed container in food packaging, in medical packaging, in analytic devices, or similar applications.

A further aspect of the invention relates to a replication tool for producing a part with a microscale textured replica surface by replication, the replication tool comprising a tool surface defining a general shape of the part, the tool surface comprising at least on portions thereof a microscale structured master surface having a lateral master pattern and a vertical master profile, wherein said microscale structured master surface has been provided by localized pulsed laser treatment adapted to generate microscale phase explosions. Preferably, the vertical master profile has a peak-to-peak amplitude of at least 0.5μm, and the lateral master pattern has an area density of microscale master features of at least 5000/mm².

The replication tool for the replication process in question, e.g. a mould for injection moulding or a roller for extrusion coating, has a tool surface defining the general shape of the part to be formed and may be provided in a conventional manner and using conventional tooling materials as known in the art, such as tool steel or 2017 aluminium. The microscale surface structuring is applied as a post treatment of the tool surface by means of a pulsed laser directly scanned over the tool surface. A suitable pulsed laser may be, but is not limited to, an industrial picosecond-laser operating in the near infrared, such as at 1064nm. The exposure of the surface to the pulsed laser radiation is adapted to generate microscale phase explosions. This includes localised melting of tool material on the tool surface, evaporating molten tool material, and ejecting molten and evaporated material in microscale eruptions from the melt surface, thereby forming a densely packed arrangement of microscale crater-shaped depressions. The localized pulsed laser treatment is adapted to produce a micro-porous structure, wherein the micro-porous structure is formed by a densely packed arrangement of crater-shaped microscale depressions with outwardly sloped side walls. The obtained microscale structured master surface has a lateral master pattern and a vertical master profile as described above. Since the post-treatment applied here does not require the precise micro-milling of a specific pre-determined shape of the master structure, such as a regular array of micro-cones, the post-treatment may be applied using cheaper equipment. Furthermore, this post-treatment adapted to generate a microscale porous surface from microscale phase explosions is faster to apply than e.g. micro-milling of microscale features. Furthermore, as also mentioned above, the microscale phase explosions generate microscale crater-shaped depressions with sloped sidewalls that are well suited for fast replication processes, such as injection moulding and extrusion coating. Amongst others, the crater shape with sloped sidewalls facilitates easy releasing of the shaped items from the tool surface at the end of the moulding process (de-moulding).

Further according to one embodiment of the replication tool, the tool surface is made of a metal, such as aluminium or steel. The tool surface has to be suited for the fast replication processes for which the method is intended. The tool surface comprising the microscale master structure can be directly produced on a mould surface for contacting the replication material and/or on an inlay attached to the inside of a mould. It is understood that the tool surface may be broken up in sub-surfaces that form part of the mould as is customary in tool design for fast replication processes, such as injection moulding or extrusion coating. Examples of commonly used metals that are also suitable for the present invention include, but are not limited to, aluminium alloys of the types 2017, 1050 or 5754, or tool steel, such as “Sandvik Corona C60”, orvar 2343 or similar.

Further according to one embodiment of the replication tool, the microscale structured master surface is a lateral arrangement of polydisperse microscale master features. The term polydisperse refers to microscale features having varying transverse dimensions as seen in a vertical projection. Typically, the polydisperse dimensions are characterized by a statistical distribution having a centre value and a spread. The transverse dimensions may be specified as transverse linear dimensions characteristic of the lumen defined by the crater-shaped depression. Given the irregular nature of a polydisperse arrangement, transverse dimensions can also be defined in combination by specifying an area covered by the crater-shaped depression. An equivalent linear dimension characterizing a given crater-shaped depression may then be defined as the diameter of a circle with the same area. The microscale master features on the master surface are preferably densely packed, with neighbouring crater shaped depressions only being separated from each other by a ridge having a width that is comparable to or preferably less than the transverse linear dimension characterizing the crater-shaped depression.

Further according to some embodiments of the replication tool the microscale master features are crater-shaped depressions. Typically the crater-shaped depressions appear more or less circular as seen in a vertical projection. Furthermore, the crater-shape implies an outwardly sloped sidewall providing a positive release angle facilitates de-moulding of the shaped item.

Further according to one embodiment of the replication tool, the vertical profile of the microscale structured master surface has a peak-to-peak amplitude of at least 0,5μm or at least 1μm and below 30μm, below 20μm, or preferably below 10μm.

Further according to one embodiment of the replication tool, the lateral pattern of the microscale structured master surface has an area density of microscale master features of at least 5000/mm², at least 8000/mm², or at least 10000/mm². Thereby, the replication tool is particularly useful for producing parts comprising a microscale textured surface with a reasonably densely packed lateral distribution of microscale features. When using a part with such a densely packed microscale texture in flange portions for forming ultrasonic joints, high precision, fluid tight ultrasonic joints with improved bond strength are achieved.

It should be noted, however, that the process according to the present invention will not exceed an inherent upper limit for the area density of the microscale lateral structuring. Such an inherent limit is due to the fact that the microscale features produced by the microscale phase explosions according to the present invention require a minimum footprint in order to be resolved. While the present invention produces polydisperse features with a distribution that may include submicron elements, their average (most prominent) lateral dimensions are in the microscale. Increasing the area density of the microscale features results in an increasing probability for the occurrence of overlap between adjacent microscale features. Above a critical overlap, the microscale features are overlapping to such an extent that they appear merged and effectively have a much larger lateral extension than a targeted feature size of individual, unmerged microscale features. As a consequence, above a critical area density such merged features increasingly dominate the actual feature size produced on the replication tool.

In a characterization of the microscale surface structure of the master surface, e.g. by commonly known image analysis techniques applied to micrographs thereof, the merged features are then counted as a single feature with a larger lateral dimension or foot print. This effect is best seen in a graph showing the area density of microscale features, e.g. counted in a given surface portion by means of image analysis, as a function of the laser energy exposure applied to that surface portion. By way of example, such a graph is shown in Fig.19. The data shown has been obtained by an analysis of the microscale structuring applied to more than 70 replication tool blanks (tool grade aluminium as specified elsewhere in this application) using the method according to the invention. The ordinate shows the exposure dose expressed in terms of the number of repetitions divided by the scan speed; the coordinate shows the area density of holes detected by an image analysis performed on micrographs of the processed surface; and the marker size indicates the size of the detected feature determined by the same image analysis algorithm. In an initial regime at low exposure, the individual microscale features are resolved and all have essentially the same size. The initial regime covers a low density regime up to about 5000/mm^2 where the distribution of the microscale features may be considered as sparse. In an intermediate exposure regime above about 5000/mm^2, the microscale features may be considered as more and more densely packed, reaching a critical density of about 12000/mm^2, where overlap of adjacent microscale features begins to become significant. The critical density is the maximum achievable density for a given system, which in the example of Fig.19 is about 12000/mm^2. Other material systems and laser processing set-ups may have a different maximum achievable area density, such as about 100000/mm^2, or about 50000/mm^2, or 20000/mm^2, or about 15000/mm^2. An inherent limit to the maximum achievable area density is given by the requirement of microscale dimensions of the lateral structuring as achieved by the present invention. Increasing the exposure beyond the critical value then only results in merging of the microscale features and in a deterioration of the desired patterning. In the example of Fig.19, a significant decrease of the area density of microscale features to below 5000/mm^2, accompanied by a corresponding increase of the average feature size is observed. When the microscale structure of the replication tool master surface is transferred onto a replicated item to form a microscale surface texture for the enhancement of a wetting behaviour, a sparse distribution of microscale features may prove insufficient to provide a significant wetting behaviour enhancement – if any at all. In a preferred exposure regime around the maximum achievable area density of about 100000/mm^2, or about 50000/mm^2, or 20000/mm^2, or about 15000/mm^2, or about 12000/mm^2, the microscale features are adequately dimensioned in their lateral extend, yet are packed sufficiently dense so as to achieve a significant wetting behaviour enhancement. An adequate range may be determined by an exposure experiment as outlined in Fig.19, wherein preferably the area density is at least 60%, at least 70%, at least 80%, or at least 90% of the maximum achievable area density of microscale features. Above a critical exposure, in the regime where merging becomes more and more dominant, the wetting behaviour enhancement of the replicated item also deteriorates more and more.

Further according to one embodiment of the replication tool, the microscale master features have an aspect ratio of a vertical dimension to a lateral dimension of at least 1:2, or about 1:1, wherein the vertical dimension is the peak-to-peak amplitude and the lateral dimension is the square root of the average footprint area per microscale master feature, which for a given microscale structured surface area is calculated as the inverse of the area density of microscale master features per area, i.e. the area of the given surface in lateral projection divided by the count of microscale features in that area.

Advantageously according to a further aspect of the invention, the above-mentioned replication tool and methods are adapted such that the lateral arrangement of microscale protrusions in addition to the flange portions includes further portions on the surface of the first part. Thereby the further portions on the surface of the first part may be functionalised by applying a microscale textured replica surface to these further portions in the replication process. The replication tool is adapted by applying the above-mentioned laser treatment to generate microscale phase explosions also to further portions on the tool surface, in addition to flange portions. The parameters of the laser treatment may be kept the same or set differently for different portions of the tool surface to generate different microscale structured master surface portions depending on the purpose of the respective portions of the microscale textured replica surface to be produced therefrom. The purpose for the microscale texturing of the replicated flange portions is to act as energy directors, whereas the purpose of the microscale texturing of the replicated further portions may be another functionalization. In particular, a microscale textured replica surface produced according to any of the herein disclosed methods also exhibits enhanced wetting properties. For example, the microscale textured replica surface may exhibit enhanced hydrophobicity or even superhydrophobicity, provided that the surface material is hydrophobic. Alternatively, a microscale textured replica surface produced according to any of the herein disclosed methods may also exhibit enhanced hydrophilicity, provided that the surface material is hydrophilic.

The term “wetting properties” refers to the interfacial interactions in a system comprised of three states of matter, a solid, a liquid, and a gas, and can be quantified by a contact angle. The line connecting all three interfaces, e.g. solid-liquid, solid-gas, liquid-solid, is denoted the three phase-contact line. The contact angle is defined as the angle between the tangents of the liquid-gas and the liquid-solid interphases perpendicular to the three-phase line at any intersection of the two tangents on the three phase line. The wetting properties between a solid and a liquid in a three phase system are considered enhanced with respect to the wetting properties of a flat surface if the apparent macroscopic contact angle is altered by the structure on the surface, wherein the wetting properties of a system with a solid-liquid contact angle smaller than 90° (philic behaviour) is considered enhanced if this contact angle is reduced by the modification (philic enhancement). Likewise, the wetting properties of a system with a solid-liquid contact angle greater than 90° (phobic behaviour) is considered enhanced if this contact angle is increased by the modification (phobic enhancement).

In some embodiments, the laser treatment of the tool surface may be the same for all portions, since the microscale texturing may simultaneously act as microscale energy directors and provide enhanced wetting properties as compared to a flat unstructured surface of the surface material. Alternatively in some embodiments, the laser treatment of the tool surface may be varied for different portions thereof. For example, the laser treatment of flange portions may be optimised for the purpose of forming energy directors for use in the formation of an ultrasonic joint, whereas the laser treatment of further portions of the tool surface may be optimised for producing enhanced wettability on the further portions of the replicated part.

Advantageously according to some embodiments, the further portions of the microscale textured replica surface on a formed item are adapted to exhibit enhanced hydrophobicity, or even super-hydrophobicity. Further advantageously the replica material is hydrophobic or the microscale textured replica surface is covered with a hydrophobic layer.

Alternatively according to some embodiments, the further portions of the microscale textured replica surface on a formed item are adapted to exhibit enhanced hydrophilicity, or even super-hydrophilicity. Further advantageously the replica material is hydrophilic or the microscale textured replica surface is covered with a hydrophilic layer.

The microscale texturing of the replicated first part produced by replication from a microscale structured master surface on a replication tool may thus serve multiple purposes. This may e.g. be useful in providing a packaging having a functionalised surface, such as a superhydrophobic surface, and at the same time allowing for a formation of a precise and reliable ultrasonic joint with a high degree of design freedom. In a further example, such a dual use of the microscale texturing applied to flange portions and further portions may be useful in microfluidics, when forming sealed channels and/or reservoirs that may thus be provided with inner surfaces with an enhanced wettability, such as enhanced hydrophobicity or enhanced hydrophilicity as explained above.

In the context of this application, a material is referred to as hydrophobic, if a flat surface thereof is characterized by a water contact angle of above 90 degrees, such as above 95 degrees, such as about or above 100 degrees. Accordingly, a material is referred to as hydrophilic, if a flat surface thereof is characterized by a water contact angle of below 90 degrees, such as below 85 degrees, such as about or below 80 degrees. For example, a flat surface of the hydrophilic plastics material acrylonitrile butadiene styrene (ABS) may have a water contact angle of about 81 degrees.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the invention will be described in more detail in connection with the appended drawings, which show in

FIG. 1a-c SEM micrographs of a microscale structured master surface at different magnifications,

FIG. 2a-c SEM micrographs of a microscale textured replica surface at different magnifications,

FIG. 3 a SEM micrograph of another microscale structured master surface,

FIG. 4 a SEM micrograph of the microscale textured surface of an injection moulded item (polypropylene) using an isotherm process,

FIG. 5 a SEM micrograph of the microscale textured surface of an injection moulded item (polypropylene) using a variotherm process,

FIG. 6 schematically, the surface modification of a tool surface by pulsed laser treatment to generate microscale phase explosions,

FIG. 7 schematically, an injection moulding process according to one embodiment of the invention,

FIG. 8 schematically, an extrusion coating process according to a further embodiment of the invention,

FIG. 9 schematically an ultrasonic welding process according to one embodiment of the invention,

FIG. 10 schematically an assembly formed using an ultrasonic welding process as shown in Fig.9,

FIGS.11–14 four graphs plotting hole size and hole density on a microscale structured master surface for different parameter settings of the pulsed laser treatment of the tool surface, and in

FIGS.15–18 four graphs plotting hole density on a number of microscale structured master surfaces against the scan speed used during the pulsed laser treatment of the respective tool surfaces;

Fig. 19 a graph plotting hole density on a number of microscale structured master surfaces against the exposure in terms of repetitions divided by scan speed used during the pulsed laser treatment of the respective tool surfaces;

Figs. 20a-d SEM micrographs of
(a) cone like protrusions in an al2017 mould at a 30° view angle,
(b) cone like protrusions in an al2017 mould at a 0° view angle,
(c) replication of the al2017 mould in cyclic olefin copolymer, and
(d) an orvar2343 steel surface modified using the presented technology as seen at an 0° view angle;

Fig. 21 Schematic drawing of a high aspect ratio chip;

Fig. 22 Actual dimensional data obtained by confocal microscopy on the chip of Fig.22, overlaid with the nominal dimensional data as obtained from the corresponding CAD-design;

Figs. 23a-d - (a-d) SEM micrographs of
(a), (c) a laser modified mould on indicated length scales,
(b), (d) the corresponding injection moulded piece seen at 30° tilt,
- (e-f) optical micrographs of
(e) unbonded microscale structured energy directors, and
(f) an ultrasonic welding seam using the energy directors,
- (g-h) cross-sectional SEM micrographs of
(g) a chip prior to ultrasonic bonding, and
(h) an ultrasonic weld formed using the present technique.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Replication Tool

Examples of suitable materials are materials commonly used as inlays or mould materials in e.g. injection moulding or extrusion coating processes. These materials of the tool surface suited to be modified by pulsed laser treatment to generate microscale phase explosions include Aluminium alloys, such as so-called 1050 aluminium, 5754 aluminium, or 2017 aluminium, as well as tool steel, such as Sandvik corona C60 and orvar 2343.

Figs.1a-c show micrographs taken by scanning electron microscopy (SEM) of an aluminium tool surface, more particular a tool surface made of 2017 aluminium, which has been modified by pulsed laser treatment using a picosecond laser with a maximum power output of 50 W operating at a pulse frequency of 200 kHz and at a wavelength of 1064 nm. The surface was scanned repetitively at a given power setting in per cent of the maximum power output and with a given speed. The laser beam was incident on the tool surface in a vertical direction, wherein the laser was slightly defocused by shifting the focal point by 1,3mm in a vertical direction with respect to the tool surface to be modified. While the apparent spot size was about 50µm on the surface, a line scan of the laser produced a modified trace width of about 10µm ± 5µm. A broader trace as the one shown in Fig.1a and 1b was obtained by a meander line scan with adjacent legs of the meander shifted in a direction perpendicular to the scanning direction. Thereby an arbitrary area can be covered by a microscale surface structure. As best seen in Fig. 1a, the laser treatment results in an ablation of some of the tool surface material. The parameters of the pulsed laser treatment are, however, adjusted such that the bottom of the trace exhibits a lateral arrangement of polydisperse microscale master features, see e.g. Fig.1b. The microscale master features obtained by this pulsed laser treatment are crater-shaped depressions. The crater-shaped depressions at the bottom of the trace are a consequence of the localized pulsed laser treatment generating microscale phase explosions.

Fig. 3 shows a SEM micrograph of tool surface made of tool steel, more particular Sandvik corona C60 tool steel, which has been modified by pulsed laser treatment using the same picosecond laser with a maximum power output of 50 W operating at a pulse frequency of 200 kHz and at a wavelength of 1064 nm. Again, the surface was scanned repetitively at a given power setting in per cent of the maximum power output and with a given speed. The laser beam was incident on the tool surface in a vertical direction, wherein the laser was slightly defocused. Also here, the localized pulsed laser treatment generates microscale phase explosions resulting in a lateral arrangement of polydisperse microscale master features, wherein the microscale master features are crater-shaped depressions.

Replicated Item

Figs. 2a-c show an example of a microscale textured replica surface on a mould insert for injection moulding, as observed in a scanning electron microscope at different magnifications, wherein the width of the image corresponds to 1.2mm in Fig.2a, 0.23mm in Fig.2b, and 0.03mm in Fig.2c. The mould insert for injection moulding was designed and fabricated in 2017 aluminium alloy (MetalCentret, Denmark) by micro milling using conventional techniques to provide a tool surface defining the general shape of the part to be fabricated. To create the microscale structured master surface on the tool surface, a 1064nm, 200kHz, 50W (max power) picosecond laser (FUEGO, Time Bandwidth) mounted in a microSTRUCT vario (3D-Micromac AG) was used to generate microscale phase explosions on the tool surface, thereby producing a densely packed lateral arrangement of microscale crater-shaped depressions. The area intended for structuring was irradiated by the laser in parallel lines separated by 20 µm. In the example shown in Figs.2a-c, this pattern was repeated 20 times, and the laser power was set to 25% of the max power. Focus was offset by +1.3 mm above the surface. The microscale structured master surface produced in this example consisted of 10 lines (200 µm wide) and was 305.5 mm long. The part with the microscale textured replica surface thereon was replicated from this replication tool with the microscale structured master surface on its tool surface using a Victory 80/45 Tech injection moulder (Engel, Schwertberg, Austria). The polymer substrate used for injection moulding was cyclic olefin copolymer (COC) TOPAS grade 5013L-10 (TOPAS Advanced Polymers, Düsseldorf, Germany) with a glass transition temperature (Tg) of 135 C. Injection temperature of the polymer was 270 C and the mould temperature was kept stable at 120 C. The injection moulding was performed in isothermal mode. The resulting microscale surface texturing is depicted in Figs.2a-c. The microscale textured replica surface on this first part is adapted to act as microscale energy directors for forming an ultrasonic welding joint with a cooperating second part.

Further examples for the microscale textured replica surface on replicated parts are given in Figs.4 and 5. To produce these replica surfaces, the laser structured aluminium insert was installed in a Victory 80/45 Tech injection moulder (Engel). The polymer substrate used for injection moulding polypropylene HD120MO (Borealis) with a Heat Deflection Temperature (0.45 N/mm²) of 88 °C. Injection temperature of the polymer was 255 °C with an injection pressure of 1200 bar. Both variotherm and isotherm injection moulding processes were tested.

Parameters specific for isotherm injection moulding:

- Temperature of microscale structured aluminium insert face = 80 °C. (constant)
- Temperature of “backside” mould = 60 °C. (constant)

Parameters specific for variotherm injection moulding:

- Temperature of structured aluminium insert face = 120 °C. (injection)
- Temperature of “backside” mould = 100 °C. (injection)
- Active cooling was applied immediately after polymer injection for the duration of the holding time (60 seconds) followed by and additional cooling time (60 seconds). This resulted in a final mould temperature of 40-50 degrees.

The respective surfaces have been characterised with respect to the shape of the microscale features on the microscale textured surface of the replicated item, see Fig.4 and Fig.5. The isothermal process results in a surface texture with rounded tops, see Fig.4, and the variothermal process results in a surface texture with a hairy appearance (“pulled polypropylene”), see Fig.5. Both surfaces faithfully replicate the lateral pattern of the master, but only provide a low fidelity replication of the vertical profile of the master. Nevertheless, both processes result in a fast replication of parts with microscale energy directors on flange portions thereof. The isothermal process is preferable for high throughput or high volume production, because the isothermal moulding process is not time limited by any process step(s) involving temperature adjustments of mould and/or mould inserts, whereas the variotherm moulding process is partially time limited by one or more process step(s) involving temperature adjustments of mould and/or mould inserts.

Replication Process

Fig.7 shows schematically an injection moulding process for producing a replicated part 4. The process uses a mould having mould parts 1a and 6, wherein mould part 6 has an insert 1b. Tool surfaces 2a, 2b, 7 define a general shape of the replicated item 4. Tool surfaces 2a, 2b are provided with microscale structured master surfaces 3a, 3b, 3c, 3d, which are replicated on the item 4 as microscale textures 5a, 5b, 5c, 5d respectively.

Fig. 8 shows schematically an extrusion coating process for coating a substrate web S, with a coating 14. The process uses a roll 11, 11a with a tool surface 12, 12a defining a general shape of the coating. The tool surface comprises microscale structured master surfaces 13, 13a, which are replicated as microscale surface texture 15 on the coating 14. A microscale structured master surface 13 may be applied directly to the tool surface 12 of the roll 11 and/or a microscale structured master surface 13a may be applied to the tool surface 12a of a replication tool insert 11a for attachment to the roll 11.

Localized Pulsed Laser Treatment Generating Microscale Phase Explosions

Fig.6 shows schematically the configuration of the set-up for localized pulsed laser treatment of a tool surface 2 on a replication tool 1 to generate a microscale structured master surface 3 by scanning a pulsed laser beam 99 over the tool surface.

EXAMPLE

The example illustrates different ways of identifying suitable laser processing parameters for modifying a given tool surface to obtain a microscale structured master surface.

Aluminium 2017 (available from “Metalcenteret” Glostrup, Denmark) was surface structured using a 1064nm, 200kHz, 50W picosecond laser (FUEGO, Time Bandwidth) mounted in a microSTRUCT vario (3D-Micromac AG). To perform the surface structuring, the area intended for structuring was irradiated by the laser in parallel lines separated by 20 µm. Every second layer was perpendicular to the previous, and so one set of perpendicular planes of lines is referred to as one “cross repetition”. The laser power was set to 25% and 10 repetitions was conducted with focus offset +1.3 mm above the surface.

As illustrated in 11-18, the average dimension and standard deviation of the hole sizes may be adjusted by varying parameters such as laser power in percent of maximum power output, scanning speed, number of cross repetitions and z offset of the focus plane. To identify the optimal parameter settings for achieving a desired hole size population and hole density in the alloy in question, one may map the parameter space of the laser settings. When replicated in polymer, the hole size population and hole density will determine the surface structure and roughness and hence the final wetting properties of the polymer piece. In the example below, the parameter space was for the

- Laser power in percent of the maximum power of 50W: from 10 to 100 (both included), in increments of 5;
- Scan Speed in mm/s: from 150 to 1950 (both included), in increments of 100; and from 600 to 4200 (both included), in increments of 200;
- Number of cross repetitions: from 3 to 39 (both included), in increments of 2;

It may be noted that similar surface characteristics may be achieved using different parameter combinations. However, to minimise time consumption for the laser process, the parameter coordinate with the highest (scan speed / cross repetition) value, and hence lowest process time, is preferred.

A recommended method to reduce the number of parameters and experiments is by locking parameter pairs in a fixed ratio, such as keeping (laser power / scan speed) constant, see Fig.11 and Fig.12, where the numerical value of the ratio of (laser power (in percent of the max power of 50W) divided by the scan speed (in mm/s) is kept constant at 25E-5 (= 0,00025) or 50E-5 (= 0,0005) and allows for identification of the desired modification characteristics: both figures show peaks in hole density X. Likewise, the numerical value of the ratio of the number of repetitions divided by the scan speed (in mm/s) can be kept constant, see Fig.13 and Fig.14, where this ratio is kept constant at 1E-2 (= 0.01) or 2E-2 (= 0.02) and allows for identifying desired modification characteristics. As can be seen in Fig. 14, the high intensity (slow speed) results in few but large holes, whereas Fig. 13 shows that for the numerical value of the ratio of repetitions over scan speed (in mm/s) equal to 0.01 a more densely packed and uniform hole formation is achieved.

Figs.15-18 show four graphs plotting hole density against the scan speed used during the pulsed laser treatment of the respective tool surfaces. At speeds ≤ 1250 mm/s, the hole density is consistent regardless of other parameters than speed, and it is concluded that writing speed is the main determining factor in this regime. At speeds ≥ 1250 mm/s, the hole density varies with the number of cross repetitions. This is true, even when the product (power X repetitions) is kept constant, (see Fig. 16). Marker size represents cross repetitions in Fig.15 and (cross repetitions X power) in Fig.16. Regardless of the parameter settings used to achieve a desired hole density, the coefficient of variance (CV) of hole size is observed to be stable in the regime where (speed ≥ 1250 mm/s), see Fig.17, and accordingly for the standard deviation (STD), see Fig.18. Marker size represents hole size CV in Fig.17 and hole size STD in Fig.18. Similarly, the laser focus parameter space may be mapped to identify applicable laser settings.

Ultrasonic Welding

Fig. 9 shows schematically a process for forming an ultrasonic welding joint between a first part 40 and a cooperating second part 50. The first part 40 is a replicated part produced using a microscale structured replication tool in a method as described before. The first part 40 has a general shape as defined by the tool surface of the replication tool. The general shape includes flange portions 41, 42 carrying microscale textured replica surfaces 43, 44 with a lateral arrangement of microscale protrusions, and a recessed portion 45. The second part 50 has cooperating flange portions 51, 52 facing towards the flange portions 41, 42 of the first part and are aligned with these flange portions 41, 42 of the first part. For welding, the first and second parts 40, 50 are brought in contact with each other such that the tops of the microscale protrusions on the first flange portions 41, 42 form point contacts with the corresponding second flange portions 51, 52. The parts are clamped in an ultrasonic tool 60, here schematically represented by an ultrasonic horn. The ultrasonic tool 60 is adapted for applying ultrasonic energy while applying a uniaxial pressure in the direction of arrow 61 across the contact interface. The ultrasonic energy is dissipated in the contact region, thereby melting the material with an axial pressure applied across the interface to form a welding joint. Fig. 10 shows schematically the assembly 90 formed by welding the first part 40 and the second part 50 together, thereby forming a cavity 95 defined by the recess portion 45 of the first part 40 and the second part 50. The second part 50 forms a lid, which is sealed fluid tight to the first part 40 by the ultrasonic welding joints 92, 94. The following is an example of a welding joint formed between a polymer part and a sheet of cyclic olefin copolymer (COC).

EXAMPLE

Ultrasonic welding of the polymer part to a 152 µm thick COC sheet (TOPAS grade 5013S-04, TOPAS Advanced Polymers) was done using a Telsonic-USP4700 ultrasonic welder (Telsonic, Herstad+Piper, Denmark). The chip welding was conducted by depositing 45 J at 90% amplitude, 20 kHz and with a normal force on the piece of 600 N. The normal force could generally be estimated from area (x y cross section) as 10 MN/m2:

area=(305.51e-3*200e-6)m2 =(6.1102e-05)m2

6.1102e-05 m2 * 10 MN/m2 = 611 N.

In a similar fashion, the amount of energy required can be estimated from the volume of the energy directors.

EXAMPLE

Referring to Figs.20-23 in the following, a detailed example is given, which shows the high precision and improved strength of fluid tight ultrasonic bonds as achieved by the invention.

The example concerns the use of microscale structured energy directors (ED) for ultrasonic welding of microfluidic systems with a lateral arrangement of microscale features, which in this example are referred to as micropillars. The micropillar EDs are produced by replicating microscale crater-shaped depressions in a mold to obtain cone like protrusion (CLP) structures on the surface of the replicated part. The microscale crater-shaped depressions are introduced on an injection mould surface using a pico-second laser and may therefore be added to any mould surface accessible to a pico-second laser beam. The technology is demonstrated on an injection moulded microfluidic device featuring high-aspect ratio ($w \times h$ = 2000 μm × 550 μm), free standing channel walls, where bonding is achieved with no detectable channel deformation. Bonding strength is similar to conventional EDs and the fabricated system can withstand pressures of over 9.5 bar.

For device fabrication based on replication techniques (e.g. hot embossing and injection moulding), the replication tool has the inverse structure and the ED structures thus have to be realized as depressions in the bottom of the cavity structure used to define the channel wall. ED structures can be realized, e.g., by micro milling, which is a rapid mould tool fabrication process, though the size of the milling tool limits the ED dimensions that can be realized. Milling tools are made as small as 10-50 μm, yet it is often not feasible to make EDs on high-aspect ratio wall structures by milling, since the drill aspect ratio is often limited to 1:3, and the micro mills are short and mounted on large shanks.

In this example, micropillar EDs are used for ultrasonic welding (UW) of microfluidic systems. The EDs are formed by introducing cone-like protrusion structures as a back-end processing of replication moulds using a picosecond laser. The micropillar EDs have the substantial advantage over traditional EDs that they can be defined on any surface accessible to a high energy pico-second laser beam. Moreover, the micropillar EDs can be introduced in designated areas on the tool, and the width of these areas can be chosen independently from the heights of the EDs contrary to traditional EDs, where larger widths are accompanied by higher structures. The CLPs are formed stochastically within the designated area exposed to the laser treatment, so only laser treatment of the general ED layout/shape is required, not an individual laser shaping of each of the individual CLPs. In the example, the technology is demonstrated for an aluminium mould. In addition thereto the CLP formation is verified for tool steel as used for high-throughput industrial moulds. To characterise the performance of the micropillar EDs, CLP-EDs are compared to micromilled EDs with respect to (1) welding strength, (2) structural deformation of a free-standing high-aspect structure, and (3) formation of particles during welding. No significant particle formation was induced by the process in the example.

Chip fabrication

Injection moulding was carried out using a custom-made moulding tool comprising a 50 mm diameter disk cavity with 12 luer inlets. The tool could be combined with mould inserts with structures machined in aluminium 2017 (al2017). Prior to injection moulding, two types of ED structures were introduced: (1) Traditional EDs introduced by micro milling using a 60° helical engraving tool (#7025, DIXI Polytool, Le Locle, Switzerland). An apex depth of 100 µm was used (width=115 µm). (2) Microstructured CLP-EDs written using a FUEGO 1064 nm, 50 W picosecond laser (Time Bandwidth, 3D-Micromac AG, Chemnitz, Germany) mounted in a microSTRUCT vario (3D-Micromac AG). CLPs were introduced by scanning the designated areas with parallel lines (10 µm spacing), repeated 20 times at 50% power and 1000 mm/s with the focus plane 1.3 mm above the surface. The writing time was 200 seconds/cm^2.

To verify that CLPs can be produced in an equivalent manner also in other industrially relevant mould materials, writing of CLPs in high performance tool steel Orvar2343 (MetalCentret, Glostrup, Denmark) was also demonstrated. Al2017 was preferred for mould making in this example, due to its ease of machining. The injection moulding was carried out on a Victory 80/45 Tech hydraulic injection moulding machine (Engel, Schwertberg, Austria) using COC grade 5013L-10 (TOPAS Advanced Polymers GmbH, Frankfurt-Höchst, Germany) with injection and mould temperatures of 270 °C and 120 °C, respectively. Injection pressure was 1766 bar.

Fabricated chips were bonded to a 500 µm thick foil of COC grade 5013S-04 (TOPAS Advanced Polymers GmbH) by ultrasonic welding. UW was performed at ambient temperature using a Telsonic-USP4700 ultrasonic welder (Telsonic, Erlangen, Germany), depositing 25 J with 75% vibrational amplitude, a trigger force of 400 N and 0.5 bar welding pressure. With the fitted 2× booster and sonotrode, the vibrational amplitudes at the sample surface were approximately 44 µm.

Bonding strength

The bonding strength was assessed using the razor-blade test based on fracture propagation developed by Maszara et al., J. Appl. Phys. 64 (1988) p.4943, and employed by Matteucci et al., Microelectron. Eng. 111 (2013) p.294, to assess the bonding strength of thermal bonding in similar chips. To perform the test, two mould inserts with a milled 5.15×42.5×0.25 mm^3 cavity were fabricated by micro milling. In this cavity, the first insert further featured a 40.5 mm long conventional ED made by conventional milling and the second insert featured a laser micromachined ED with CLPs on an area of 40.5×0.2 mm^2. The injection moulded structures were bonded to a COC foil as described above.

CLP and ED structures

Figures 20a and 20b show scanning electron microscopy (SEM) images of the CLPs written in the al2017 mould. It is noteworthy that although the laser scanning is conducted in bundles of parallel lines, the formed CLPs are stochastically formed within the laser ablated area. This may be ascribed to the fact that the microphase explosions causing the CLPs are caused by a combination of metal impurities (alloy) picking up the energy, the pulsing nature of the laser beam and non-uniformity of the laser fluence distribution. The CLPs have a typical height and spacing of 10 µm and 10 µm, respectively. On average, the CLP area protrudes 47 µm from the plane of the tool (Fig. 23g). Note that the CLPs are locally convex depressions in the mould that hence facilitate easy demoulding during replication. Fig. 20c shows a SEM image of a COC replica of the mould. The replicated structures are observed to have rounded tops due to imperfect filling during replication. We found that operating at conditions yielding higher fidelity replication resulted in more difficult demoulding due to stronger adhesion between the mould and its replica. This rounding did not affect the performance of the EDs. Fig. 20d shows tool steel Orvar2343 ablated to produce CLPs similar to those demonstrated in al2017.

Figures 23a and 23b show SEM images of the CLP-EDs in the al2017 mould for fabrication of the high-aspect ratio microfluidic system. The images clearly show the feasibility of writing CLP-ED structures at the bottom of the trenches in the mould. Note that the separation and joining of bundles of laser lines do not alter the pattern and formation of CLPs. Thus, CLP-EDs can be formed in any pattern or geometry. Corresponding SEM images of the injection moulded COC replica (Figs. 23c,d) clearly show that micropillar structures are well reproduced on the top of the high-aspect ratio wall.

Figures 23e and 23f show optical micrographs of the same structures pre and post UW. Due to the structure of the CLPs, the final micropillar CLP-EDs of the polymer chip are opaque (Fig. 23e). However, like conventional butt joint EDs, the joints are transparent post welding (Fig. 23f). It is noteworthy that no signs of trapped or compressed air are observed in structures surrounded by CLP-EDs, such as the pocket in the corner of the structure (Fig. 23e) where little or no gap is observed post UW in Fig. 23f. This indicates that the micropillar structure facilitates the escape of air during UW. SEM images Figs.23g and 23h highlight the position of CLP-ED polymer pre and post welding. Note the solidified polymer from the welding process in Fig.23h without any significant formation of “bonding flashes”. This shows the high precision achieved with the bonding method of the invention.

Bonding strength

Bonding strengths in terms of the surface energy, γ *(gamma)*, calculated from razor-blade tests are listed in Table 1.

Table 1

Bonding method	Material	γ [J/m^2]
UW, conventional EDs	COC Topas 5013L-10	100±30
UW, CLP-EDs	COC Topas 5013L-10	122±23

From the results given in Table 1 it appears that the bonding strength for thermoplastics is largest for structures bonded using ultrasonic welding. No significant difference is observed between conventional EDs and micropillar EDs.

High-aspect ratio microfluidic system

The performance of CLP-ED structures were tested in the described high-aspect ratio microfluidic system. Fig.21 shows a schematic drawing of the high aspect ratio chip with an outer channel 101, and an inner channel 102 separated by walls 103. Cross sections (I-I, II-II, III-III) for confocal imaging are indicated. A bundle of 20 laser patterning lines 104 were added on the walls 103. Note that the 20 lines 104 are separated into two bundles of 10 lines each (104a, 104b) at the corners, to keep a constant edge distance of 180µm.

First, it was verified that the microfluidic channels were leak-tight when filled with an aqueous solution containing fruit dye. Further, pressure testing with gas applied to the outer channel while leaving the inner channel at ambient pressure showed that the devices (three tested) could sustain pressure up to at least 9.5 bar (maximum pressure available in the test).

Fig.22 shows confocal imaging data (thick lines) of the free-standing wall structures of the device along the cross sections 1-3 (cf. Fig. 21). The data of the three sections taken along the length of the parallel channel section (I-I, II-II, III-III) are overlaid on each other and fully coincide. The confocal imaging data are further overlaid with the corresponding CAD file used for the mould fabrication. From the confocal images, it is derived that the channel height of the welded structure matches that of the design (2000 µm) with a tolerance of ±4.2 µm. This value is smaller than the confocal image voxel height and we conclude that any height difference is below our detection limit. This data further supports the particularly high precision of the bonding method according to the present invention.

In conclusion, the present example shows ultrasonic welding of microfluidic systems based on micropillar EDs according to one embodiment of the invention. The micropillar EDs are produced by replication of CLPs in aluminium, formed using a picosecond laser, and can be added to any mould surface accessible to a high power pico-second laser. The example demonstrated the technology by injection moulding microfluidic devices featuring high-aspect ratio structures and shown that ultrasonic welding of the devices is possible with no detectable channel deformation. The performance of the CLP-EDs was characterised showing that bonding strength is similar to conventional EDs, with no particle formation. The bonded devices could withstand 9.5 bar of hydraulic pressure without fracturing. The laser processing method has further been demonstrated to work in high endurance tool steel used for making high performance injection moulding tools. Furthermore, the method of the invention supports a modification rate of 200 seconds/cm^2 and post processing capabilities on full three-dimensional mould surface shapes, as long as these are optically accessible.

CLAIMS

1. Method of producing a first part having a flange portion for use in the formation of an ultrasonic welding joint with a cooperating second part, the method comprising the steps of
   - providing a forming tool having a tool surface adapted to define a general shape of a part to be formed;
   - modifying at least portions of the tool surface by a pulsed laser treatment to obtain a replication tool with a microscale structured master surface with a lateral master pattern and a vertical master profile; wherein the pulsed laser treatment is adapted to generate microscale phase explosions on the tool surface, thereby forming the microscale structured master surface as a lateral arrangement of microscale crater-shaped depressions; and
   - using the replication tool to form the first part by the replication process, wherein the formed first part has the general shape defined by the tool surface, and wherein the formed first part comprises a microscale textured replica surface with a lateral arrangement of microscale cone-like protrusions produced by the microscale structured master surface on at least the flange portion of the first part, wherein the lateral pattern of the microscale textured replica surface has an area density of microscale cone-like protrusions of at least 5000/mm².

2. Method according to claim 1, wherein the replication process is one of injection moulding, hot embossing, compression moulding, and extrusion coating.

3. Method according to claim 1 or claim 2, wherein the microscale textured replica surface has a peak-to-peak amplitude of at least 0.5μm, or at least 1μm and up to 5μm, or up to 10μm, or even up to 30μm.

4. Method according to any of the preceding claims, wherein the lateral pattern of the microscale textured replica surface has an area density of microscale cone-like protrusions of at least 8000/mm², or at least 10000/mm².

5. Method of joining a first part and a second part by ultrasonic welding, the method comprising the steps of

- producing the first part with microscale energy directors on a flange portion thereof by the method according to any one of claims 1-4;

- producing a second part having a cooperating flange portion;

- bringing the microscale cone-like protrusions on the flange portion of the first part in contact with the cooperating flange portion of the second part; and

- applying ultrasonic energy and pressure, thereby flattening out the cone-like protrusions, to form an ultrasonic welding joint between the first and second parts.

6. Method according to claim 5, wherein at least one of the first part and the second part is made of a thermoplastics material.

7. Method according to claim 5 or claim 6, wherein the first part comprises a flexible web carrying the microscale textured replica surface with a lateral arrangement of microscale cone-like protrusions on at least a flange portion thereof.

8. Replication tool for producing a part with a microscale textured replica surface by replication, the replication tool comprising a tool surface defining a general shape of the part, the tool surface comprising a microscale structured master surface having a lateral master pattern and a vertical master profile, wherein said microscale structured master surface has been provided by localized pulsed laser treatment adapted to generate microscale phase explosions, wherein the vertical master profile has a peak-to-peak amplitude of at least 0,5μm, and wherein the lateral master pattern has an area density of microscale master features of at least 5000/mm².

9. Replication tool according to claim 8, wherein the tool surface is made of a metal, such as alloys of aluminium or steel.

10. Replication tool according to claim 8 or claim 9, wherein the microscale structured master surface is a lateral arrangement of polydisperse microscale master features.

11. Replication tool according to any one of claims 8-10, wherein the microscale master features are crater-shaped depressions.

12. Replication tool according to any one of claims 8-11, wherein the vertical master profile has a peak-to-peak amplitude of at least 0.8μm, preferably at least 1μm, or at least 2μm.

13. Replication tool according to any one of claims 8-12, wherein the vertical master profile has a peak-to-peak amplitude below 30μm, below 20μm, or preferably below 10μm.

14. Replication tool according to any one of claims 8-13, wherein the lateral master pattern has an area density of microscale master features of at least 8000/mm², or at least 10000/mm².

15. Replication tool according to any one of claims 8-14, wherein the microscale master features have an aspect ratio of a vertical dimension to a lateral dimension of at least 1:2, or about 1:1, wherein the vertical dimension is the peak-to-peak amplitude and the lateral dimension is the square root of the average footprint area per microscale master feature.

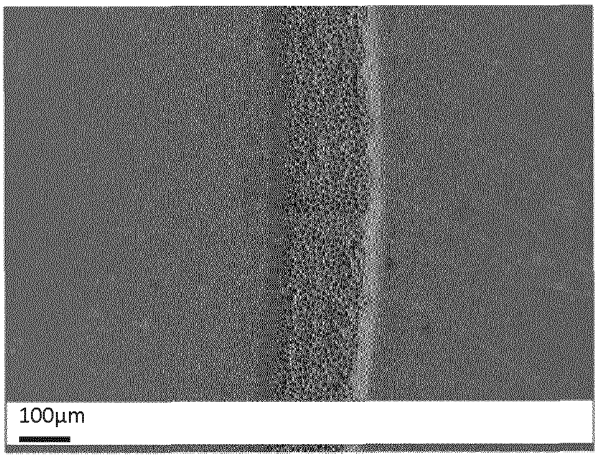


Fig. 1a

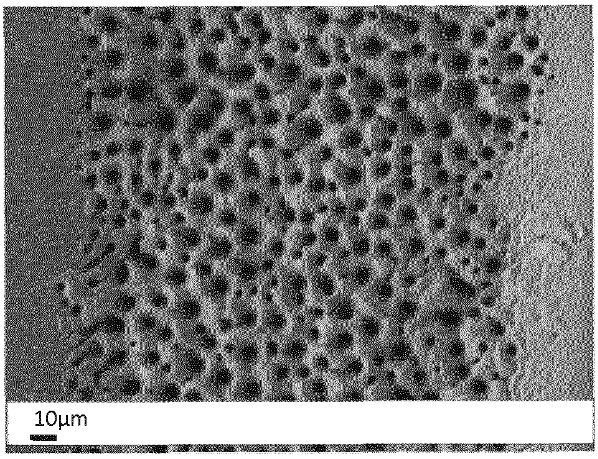


Fig. 1b

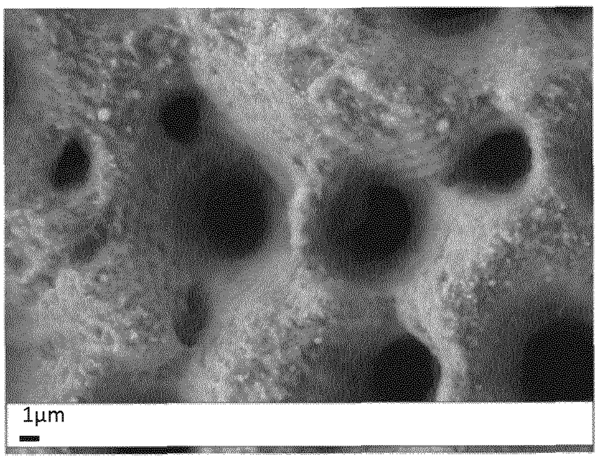


Fig. 1c

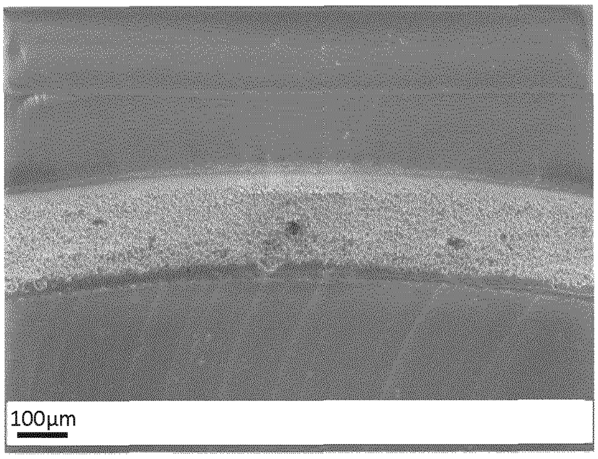


Fig. 2a

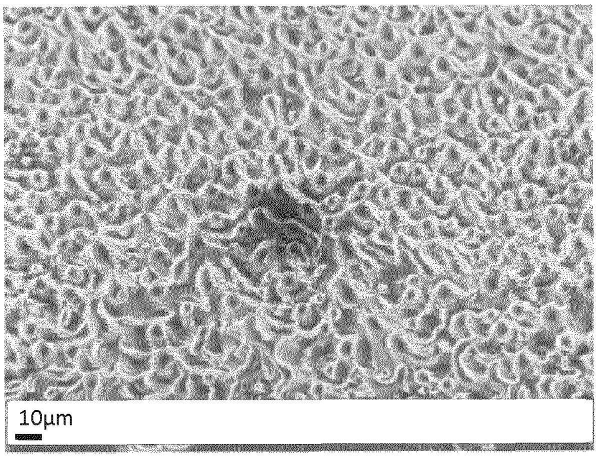


Fig. 2b

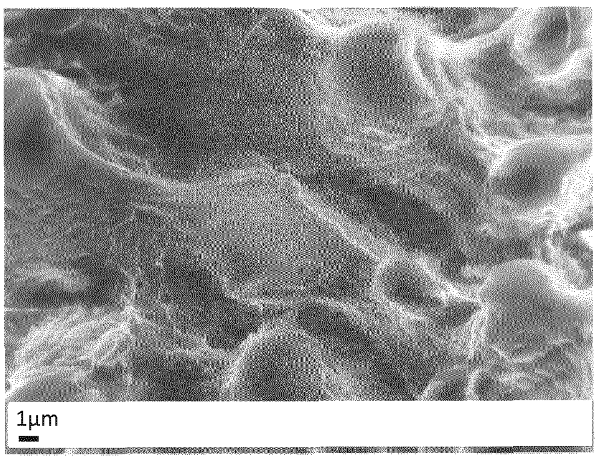


Fig. 2c

Fig. 3

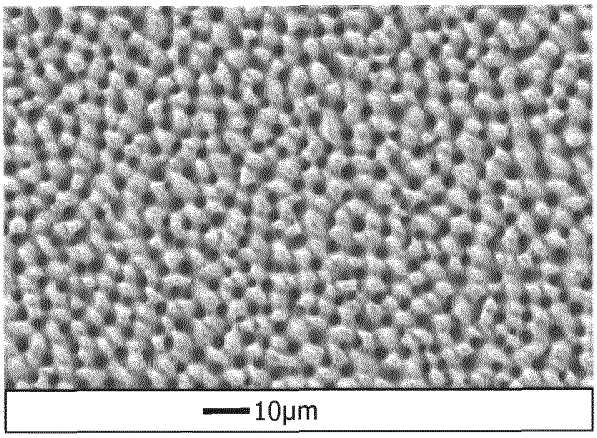


Fig. 4

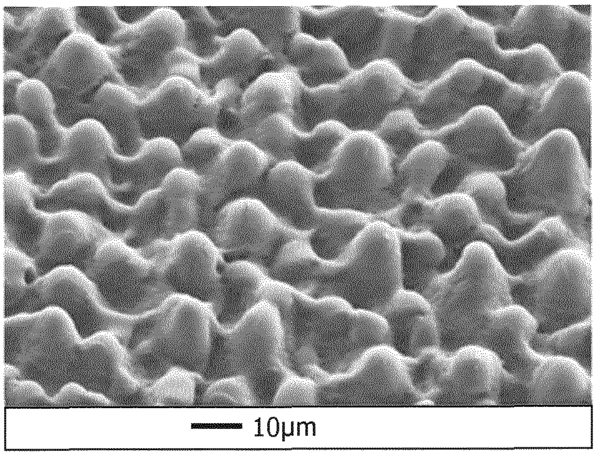


Fig. 5

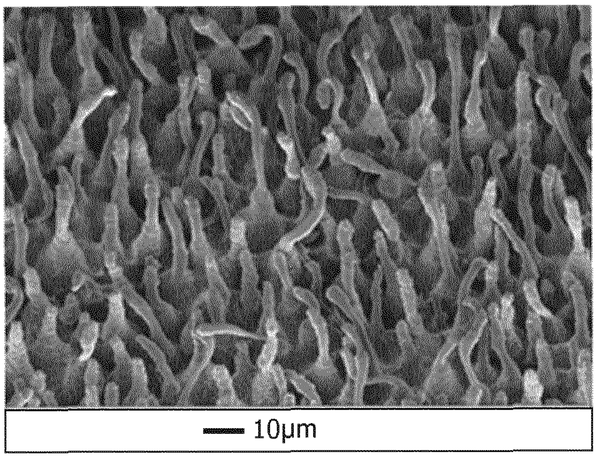


Fig. 6

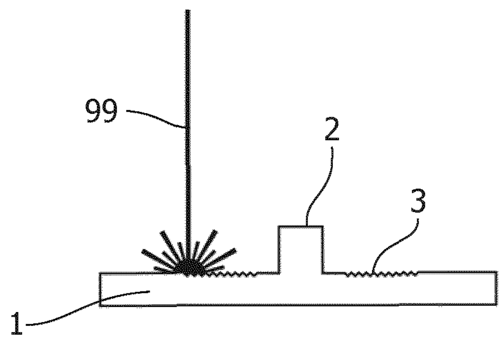


Fig. 7

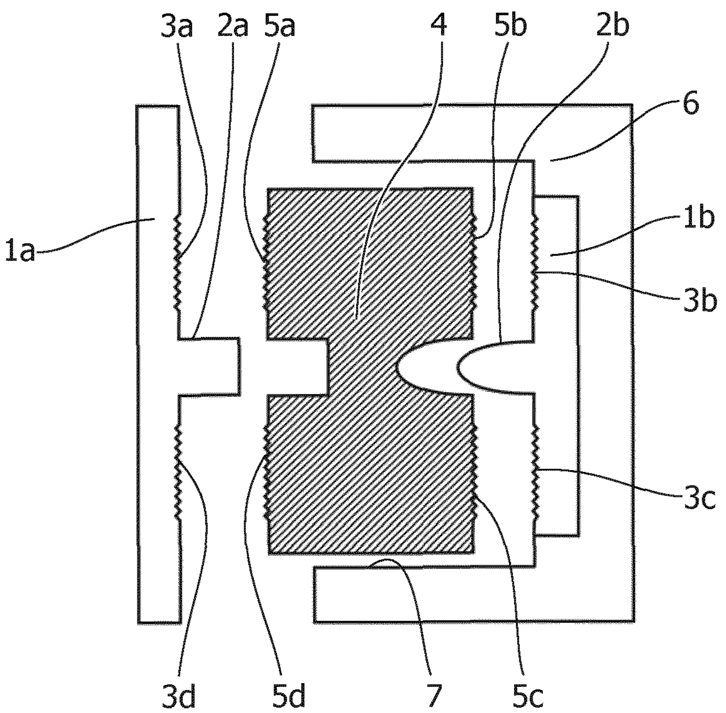
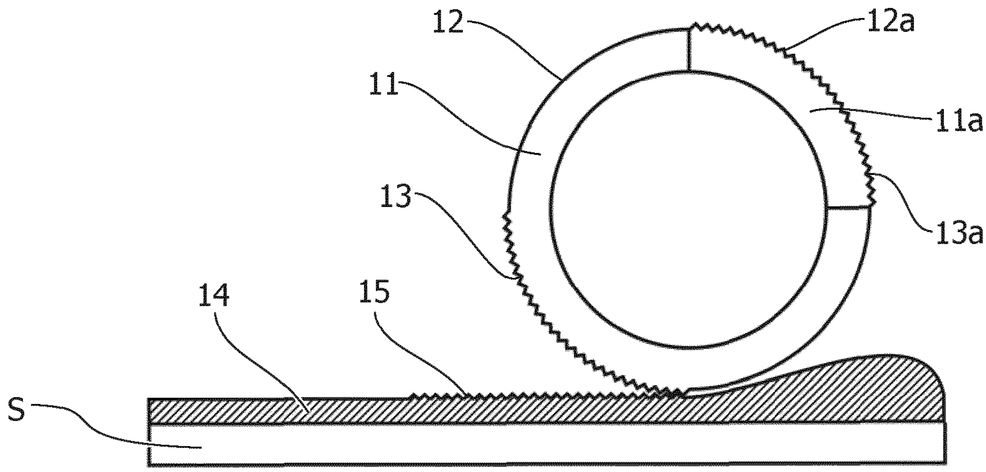


Fig. 8



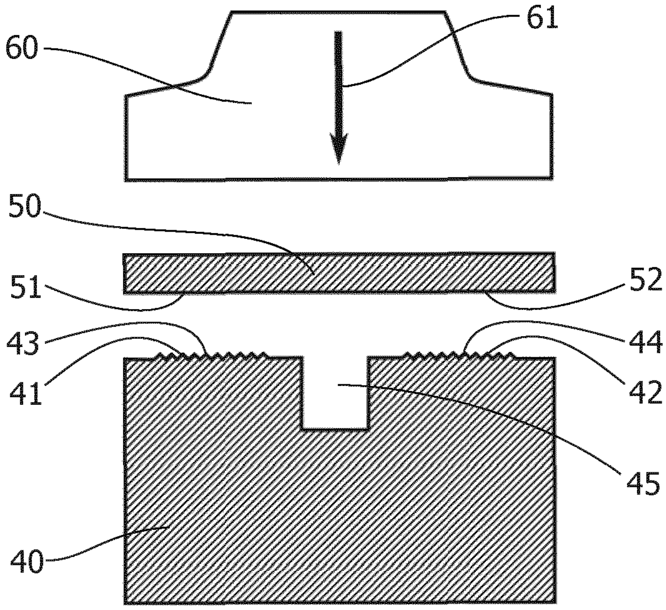


Fig. 9

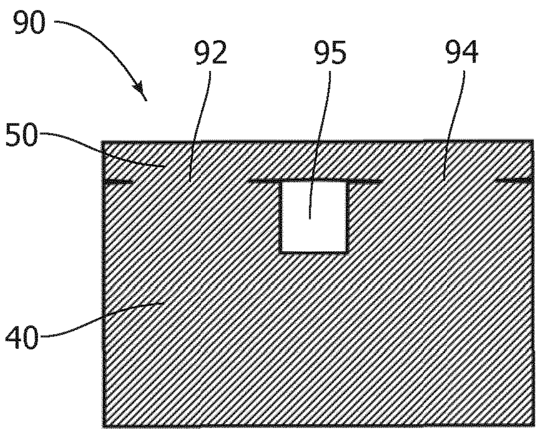
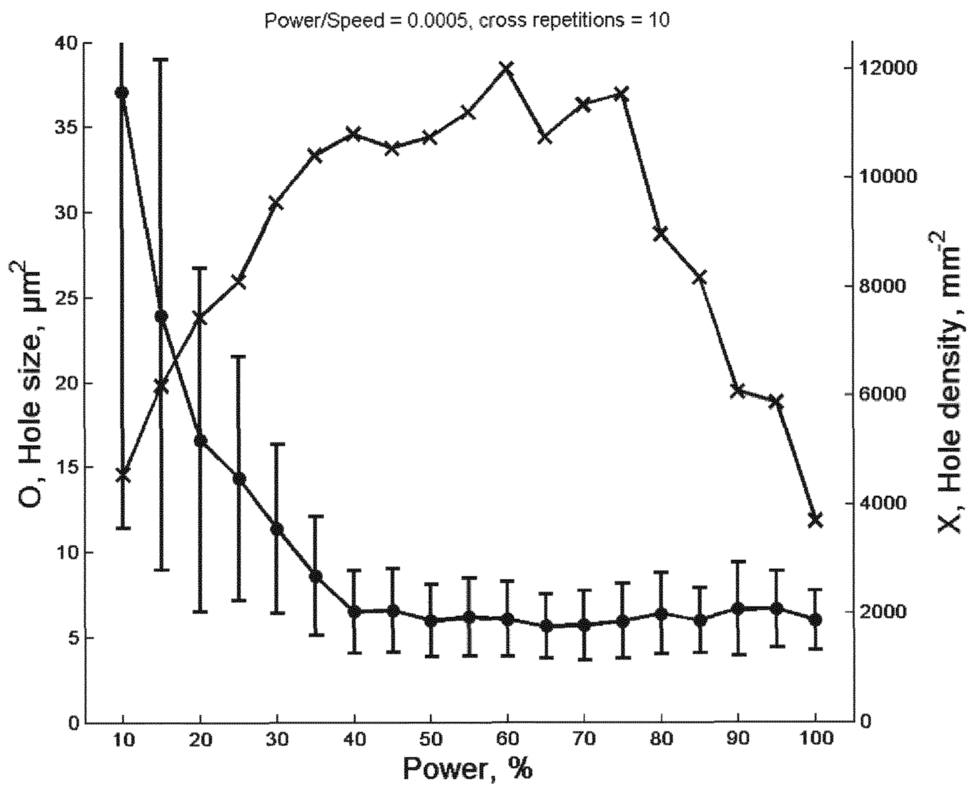


Fig. 10

Fig. 11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X, Hole density, mm-2
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100

Fig. 12

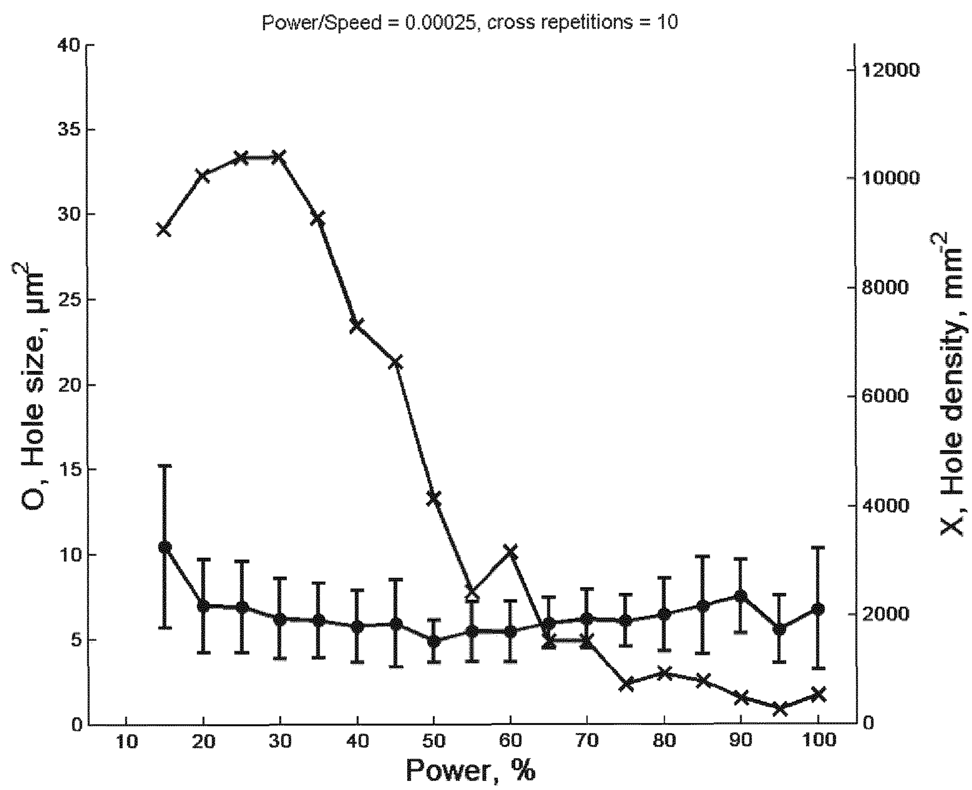
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Fig. 13

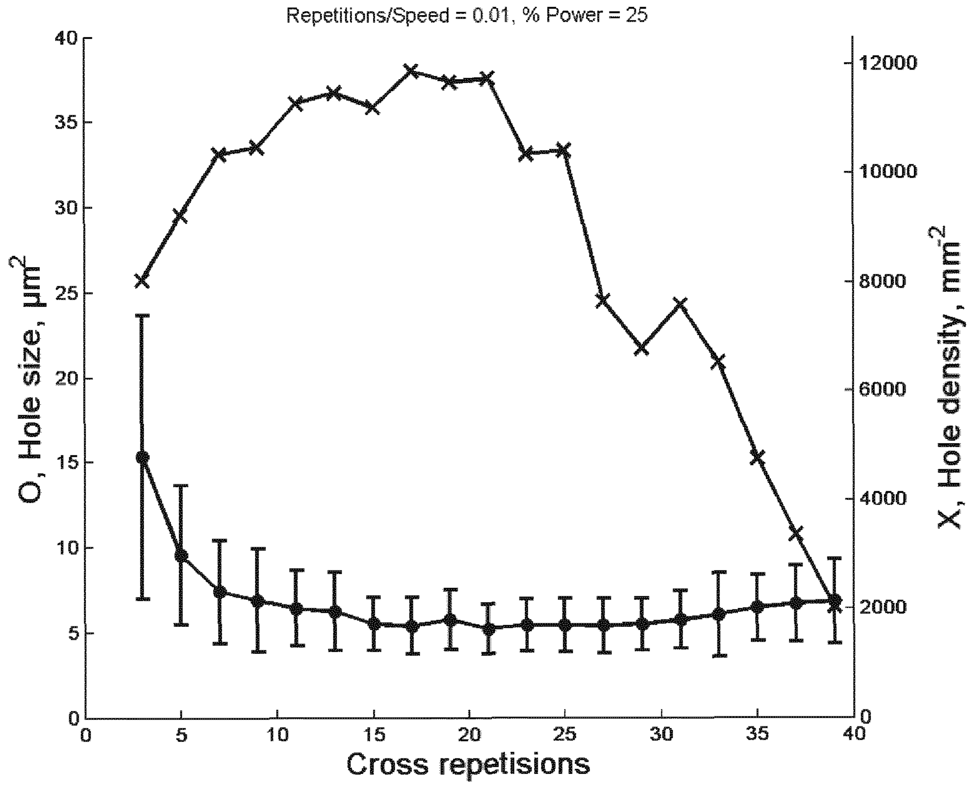
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Fig. 14

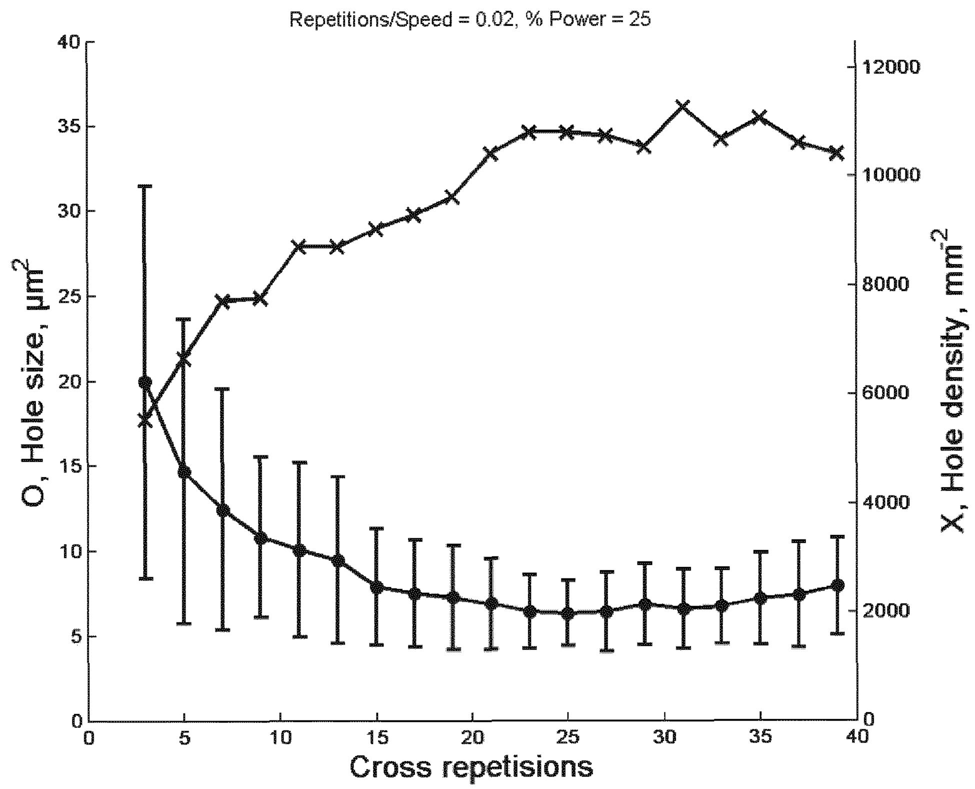
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Fig. 15

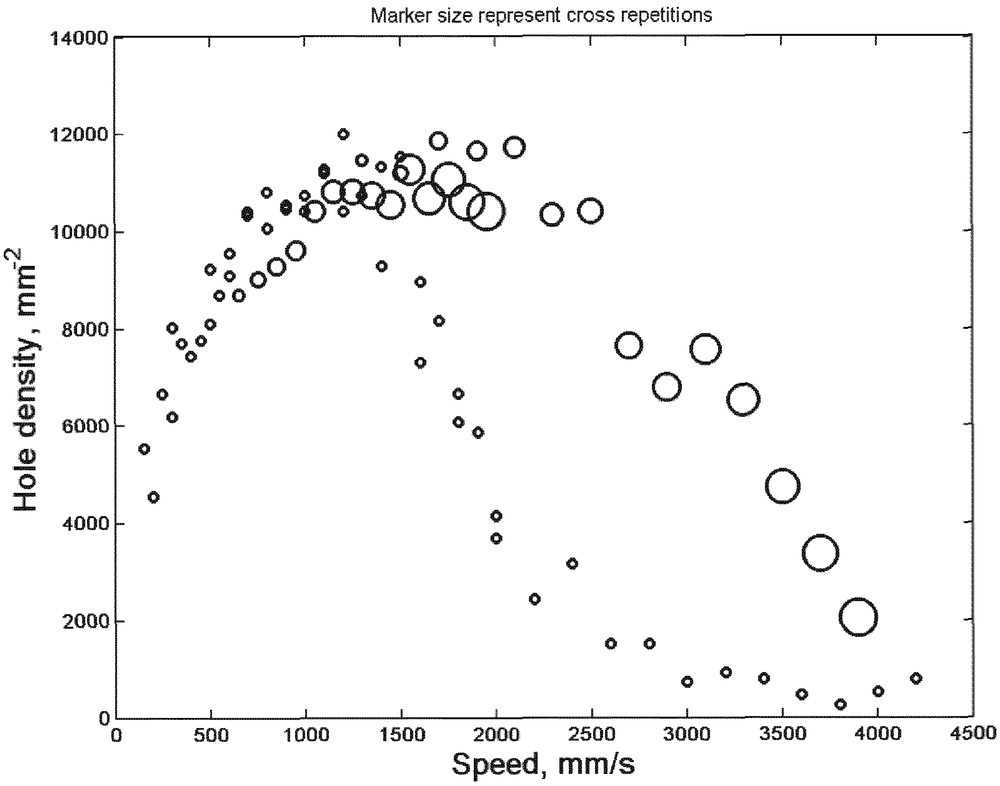
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Fig. 16

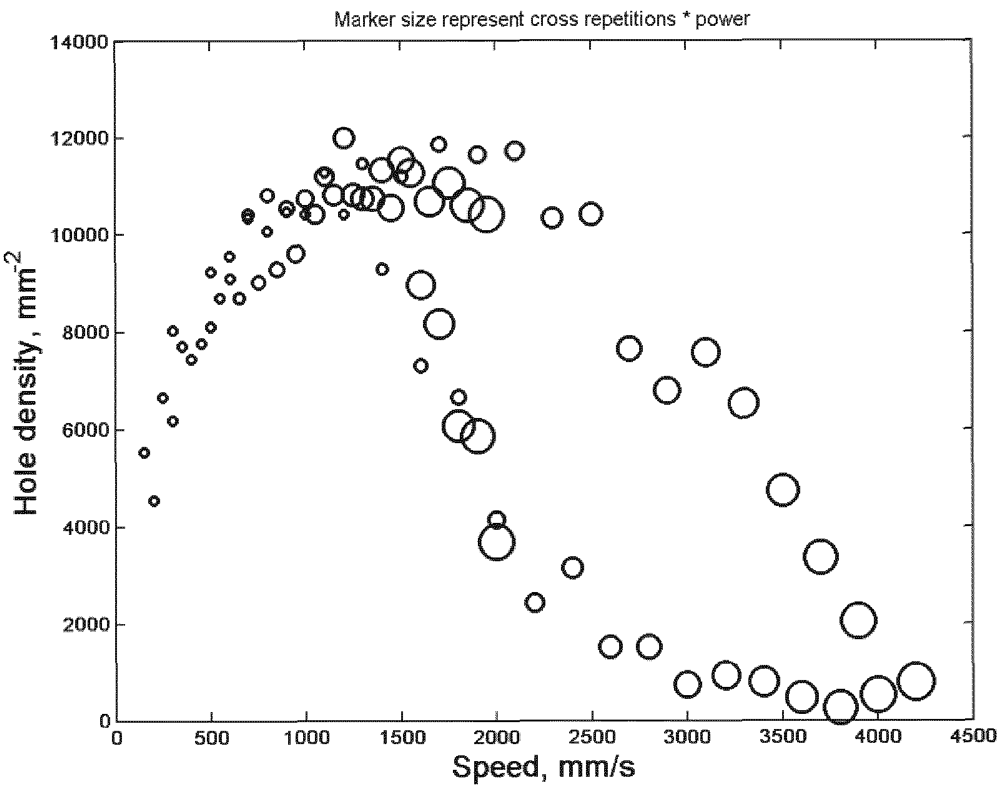
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Fig. 17

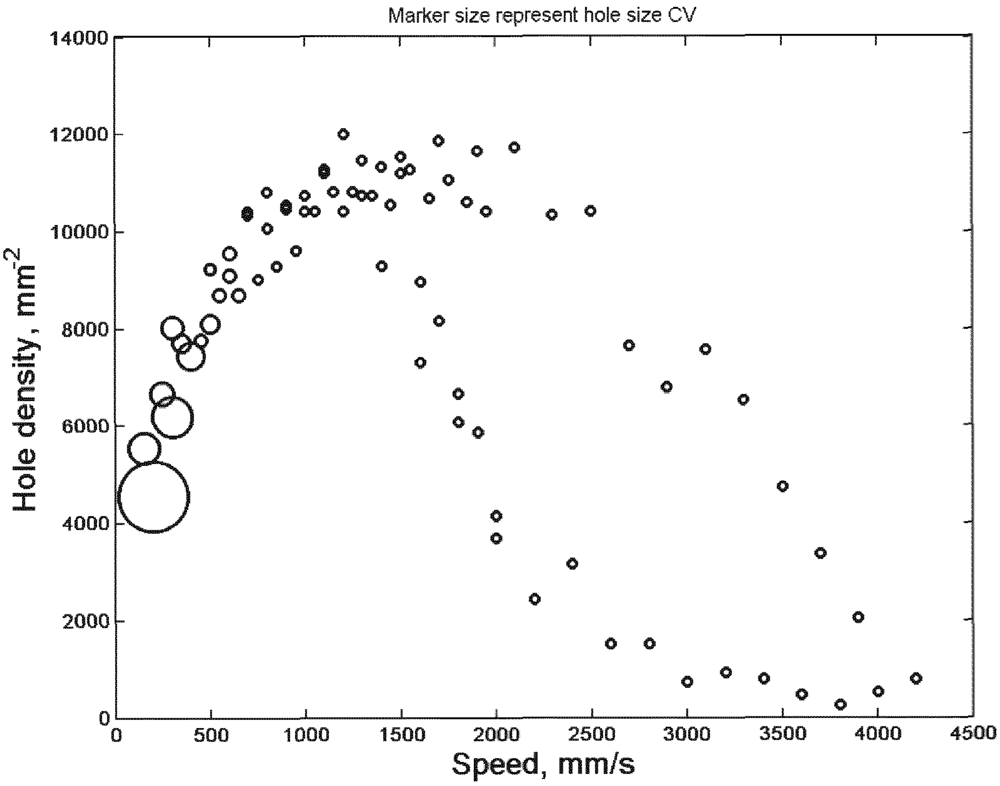
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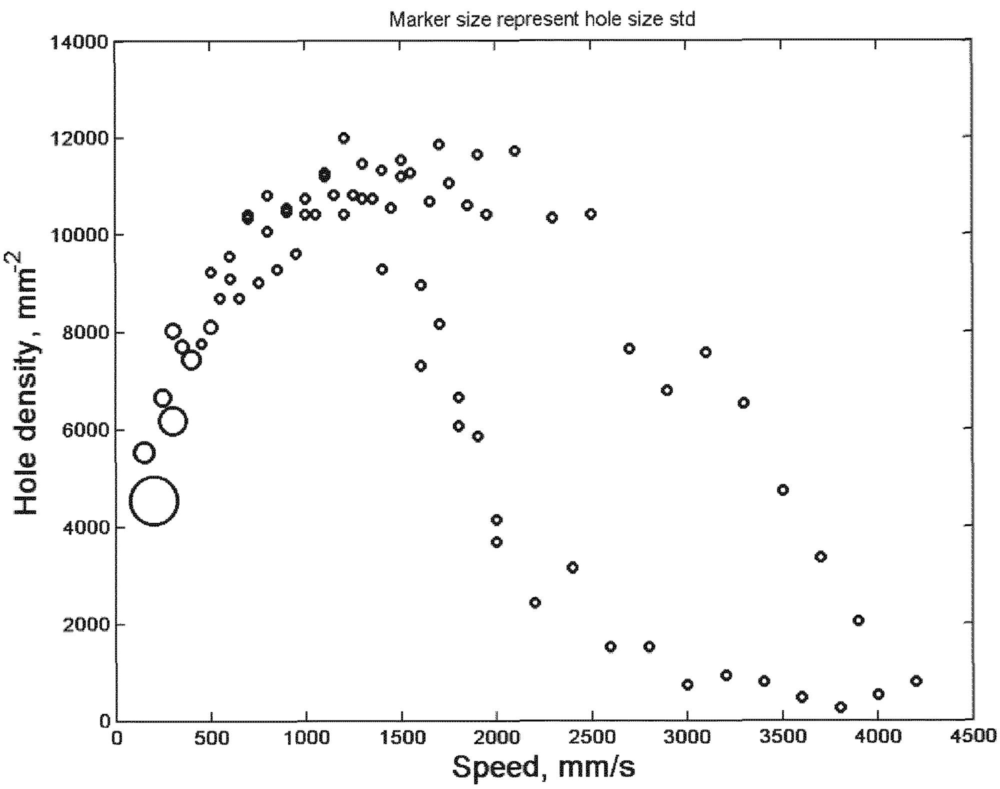
Fig. 18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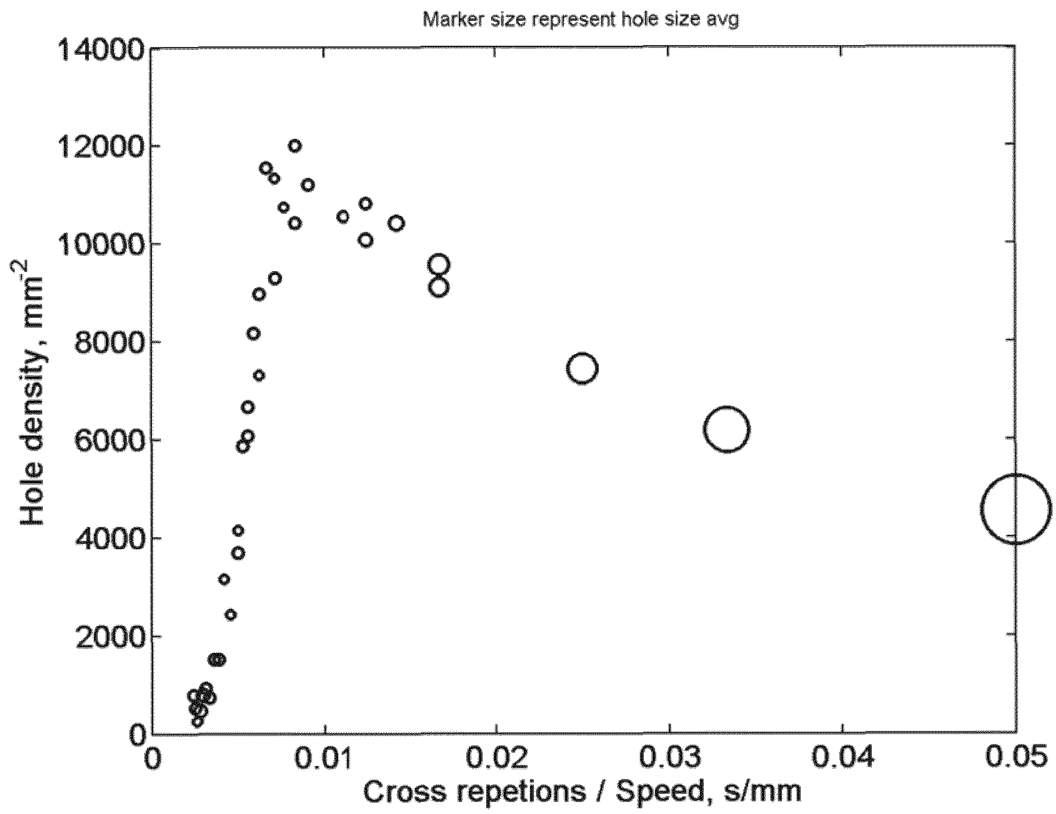
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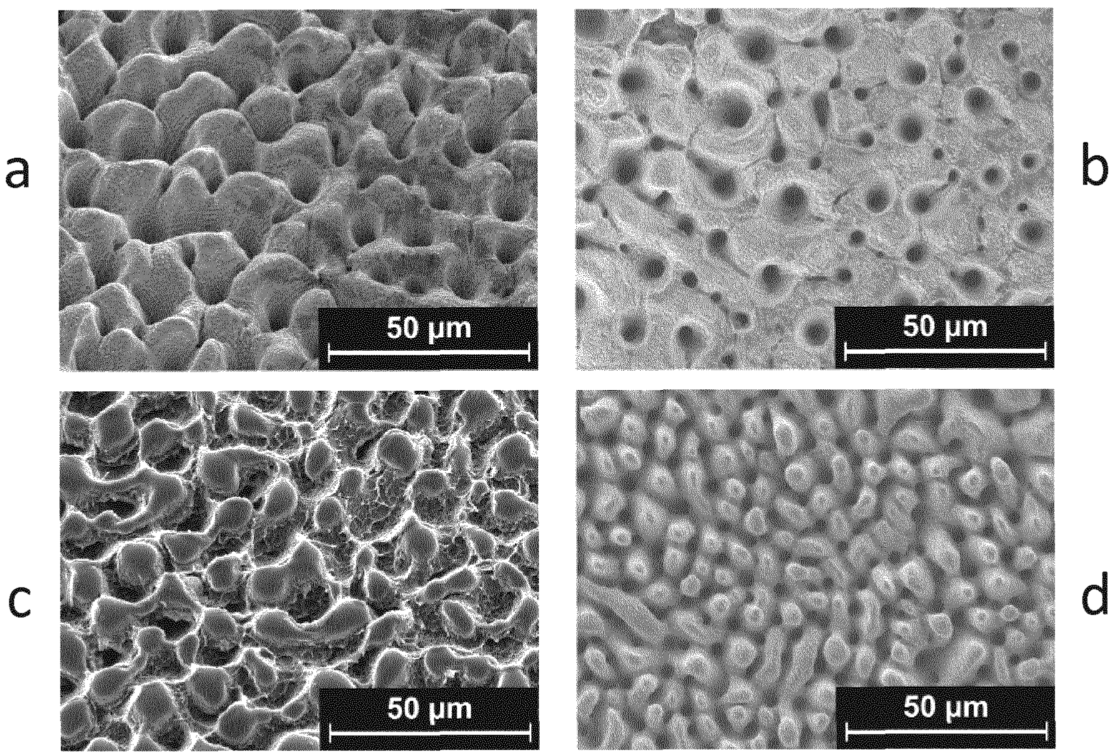
0.05

Fig. 19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b
c
d
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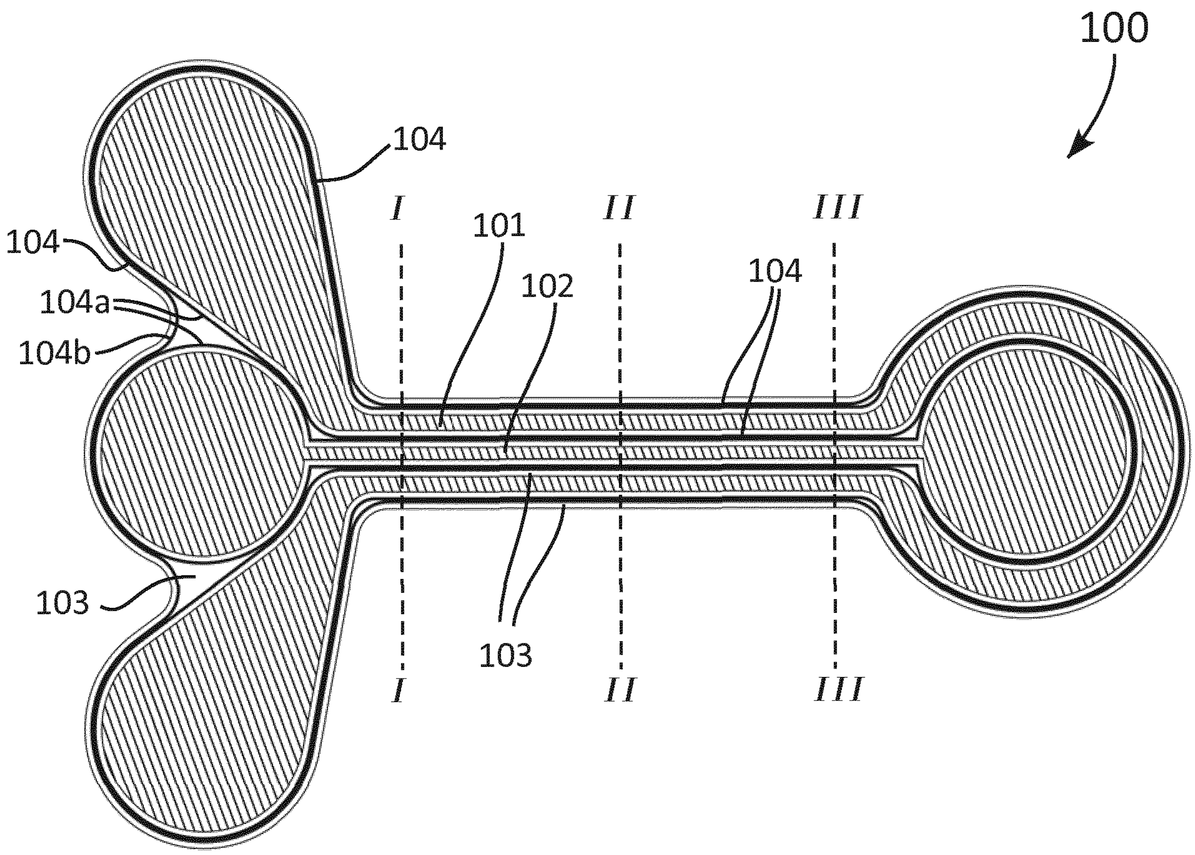
50 µm
50 µm
50 µm

Fig. 20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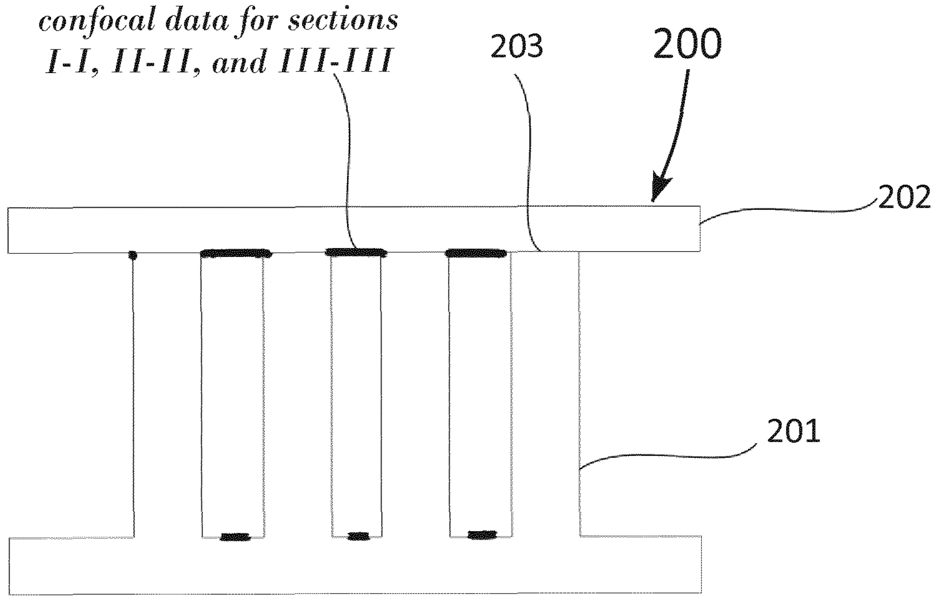
III

Fig. 21


confocal data for sections
I-I, II-II, and III-III
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200
202
201

Fig. 22

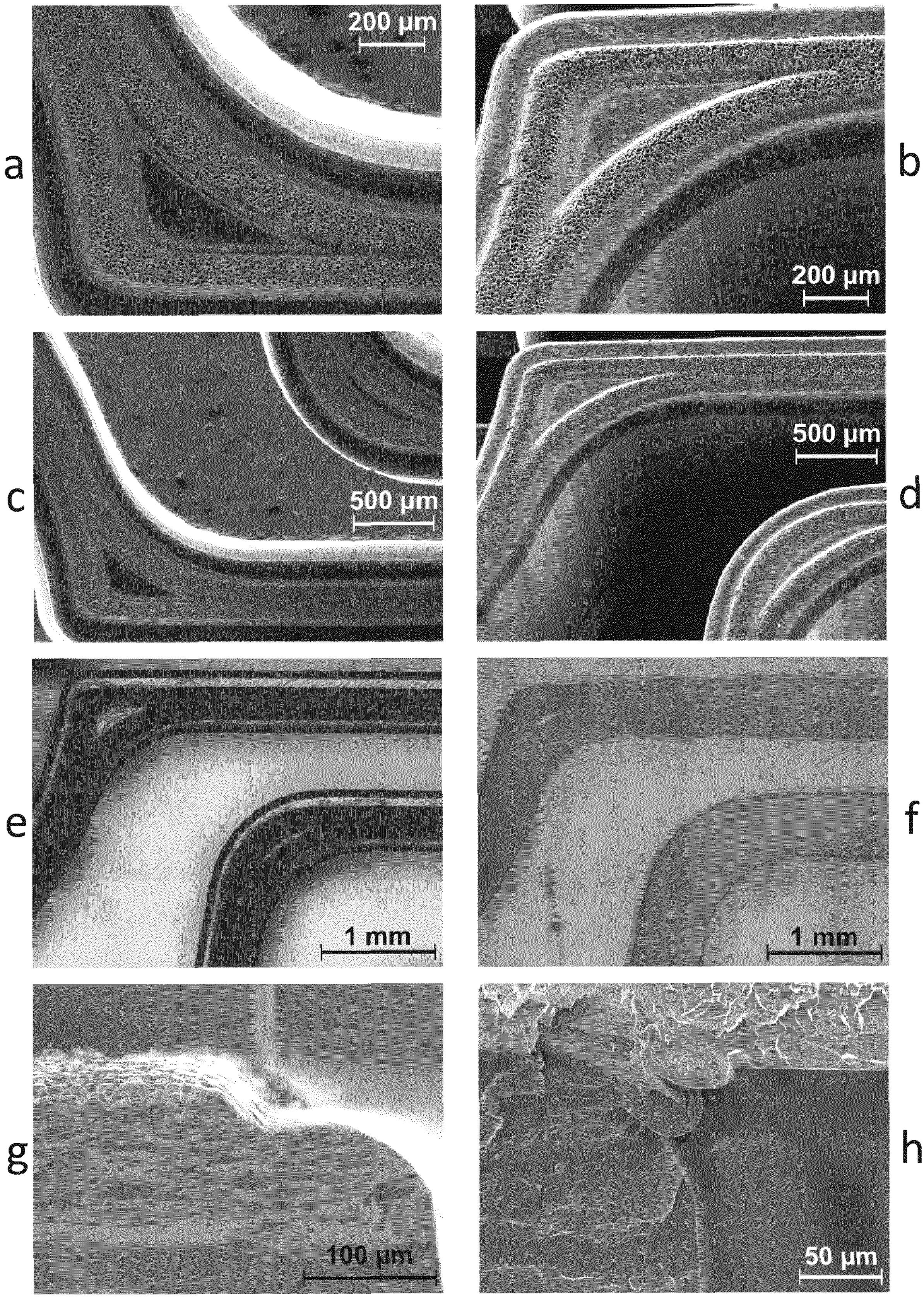

Fig. 23

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2015/076518

A. CLASSIFICATION OF SUBJECT MATTER
INV. B23K26/00 B29C33/42 B29C37/00 B29C65/08 B29C65/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B29C B23K B29L B29K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	US 2014/205801 A1 (IWATA RYOSUKE [JP] ET AL) 24 July 2014 (2014-07-24) paragraph [0001] paragraph [0220] - paragraph [0243] paragraph [0260] - paragraph [0274] paragraph [0279] - paragraph [0285] table 2 figures 3a-4,8-10c,12a-20b -----	1-4,8-15 5-7

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
15 February 2016	23/02/2016

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Fageot, Philippe

1

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2015/076518

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